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TP 6694E

FIRE TEST TO STUDY THE SIGNIFICANCE
OF A BURNING RELIEF VALVE FLARE
FROM A TANK-CAR ENGULFED
IN FIRE

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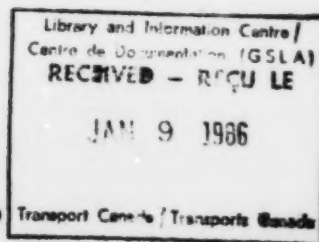
**FIRE TEST TO STUDY THE SIGNIFICANCE
OF A BURNING RELIEF VALVE FLARE
FROM A TANK-CAR ENGULFED
IN FIRE**

Prepared For:

**TRANSPORTATION DEVELOPMENT CENTRE
TRANSPORT CANADA**

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17. Abstract A fire test was performed on a scale model of a rail tank-car to study the significance of a burning relief valve flare when a tank is engulfed in fire. The test was performed as part of the validation of the Rail Tank-Car Thermal Computer Model (TNKCAR). The test involved a water-filled tank (approximately 1/5 scale) engulfed by a JP-4 fueled fire and with a propane-fueled simulated burning relief valve flare. Instruments were located to measure tank wall temperatures, tank wall heat fluxes, tank lading temperatures, fire temperatures, heat flux to remote targets, and entrained air dynamic pressures. The results of the tests indicate that, in the absence of cross wind effects, the burning relief valve flare has little or no effect on a tank that is engulfed in a highly sooty fire. However, the burning relief valve flare did affect the overall fire size and geometry, and therefore heat fluxes to remote targets were slightly increased.					
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17. Résumé Une maquette de wagon-citerne a été soumise à l'action des flammes dans le but d'étudier les conséquences de l'effet torche résultant de l'inflammation du produit sous pression évacué par les soupapes de sûreté. Cet essai faisait partie du programme de validation du modèle de simulation par ordinateur du comportement au feu d'un wagon-citerne. La maquette au 1/5, remplie d'eau, a été soumise à l'action de flammes enveloppantes alimentées par du JP-4. Pour simuler l'effet torche précité, un jet de propane enflammé a été utilisé. Des appareils avaient été disposés afin de mesurer la température des parois, les flux thermiques dans les parois, la température du contenu et celle des flammes, les transferts thermiques aux objets environnants et la pression de l'air entraîné. Les essais ont montré que, en l'absence de vents traversiers, la torche a peu ou pas d'effet sur la tenue du réservoir exposé à un feu dégageant une épaisse fumée. Par contre, elle a un effet sur l'ampleur de l'incendie et sa géométrie, stimulant de la sorte les transferts thermiques vers les objets environnants.			
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1.0 INTRODUCTION

This study was conducted as part of the validation of the Tank-Car Thermal Computer Model, DSS contract number OSD83-00086, for the Transportation Development Centre of Transport Canada. The study involved a fire test of a simulated tank-car (approximately 1/5 scale) exposed to an engulfing fire, with a simulated burning relief valve flare present.

The Tank-Car Thermal Computer Model was developed to study the effectiveness of new concepts in thermal protection for rail tank-cars. The technical details of this computer model are presented in the TDC report entitled, "User Documentation for the Rail Tank-Car Thermal Analysis Program (TNKCAR)".

The model has been validated using the results from a number of previously conducted full and fifth-scale fire tests conducted on tanks filled with propane. Details of this validation are presented in the TDC report entitled, "Validation and Testing of the Rail Tank-Car Thermal Analysis Program (TNKCAR)".

The following pages present the reasons for conducting the present test, the details of the test apparatus and instrumentation, and the test results.

1.1 BACKGROUND

Tank-Cars carrying pressurized commodities such as propane are equipped with safety relief valves which automatically open when the tank internal pressure rises above some predetermined level.

When a tank-car is exposed to an external fire environment, the tank internal pressure will rise and eventually the pressure relief valve will open. The contents of the tank will vent to the atmosphere and mix with the surrounding air. Inevitably the issuing jet will ignite and the resulting flare will become an additional heat source to the tank/lading system. The significance of the heat input from the burning flare is not known accurately at the present.

Some researchers believe that when a tank-car is already engulfed in a fire, the tank does not see the effects of the burning relief valve flare directly because of the

attenuating effects of the intervening combustion gases. A mathematical model was developed by Birk (1), which considered a tank engulfed in fire with a burning relief valve flare present. Figure 1-1 presents the basic model geometry.

The model involved an infinite cylinder surrounded by a rectangular enclosure with dimensions approximating those of the fires in the AAR-RPI Full-Scale Fire Tests (2). The rectangular enclosure was assumed to be filled with a gray absorbing gas. The burning flare was represented as a cone radiating as a black body. Radiant heat transfer between the flare and the tank top dead centre (for various axial positions) were calculated. The calculations accounted for the geometry and for the attenuation of the thermal radiation from the burning flare. Based on this model, it was concluded that the burning flare is not a significant heat input when an engulfing fire is present. However, some researchers disagree with this conclusion, and in fact some believe that the burning relief valve flare may have a significant effect on the tank failure.

The present research project was conducted to determine, under strictly controlled conditions, whether or not a burning relief valve flare is a significant heat source to a tank that is already engulfed in fire. In the present case, controlled means the fire was to be isolated from extraneous effects such as cross-wind.

1.2 SCOPE AND OBJECTIVES

The scope of the project originally involved a pool fire with a burning flare within it. Tests were to be performed with instruments located strategically so that the total fire heat flux could be measured for just the pool fire, and for the pool fire with the burning flare present.

The scope was expanded to include an instrumented simulated tank-car within the fire as shown in Figure 1-2. The researchers believed that the addition of the simulated tank would result in a more realistic test because it is known that the presence of the tank affects the flow field of the fire, and of the fuel burning rate. In addition, the simulated tank car would also act as an effective instrument support.

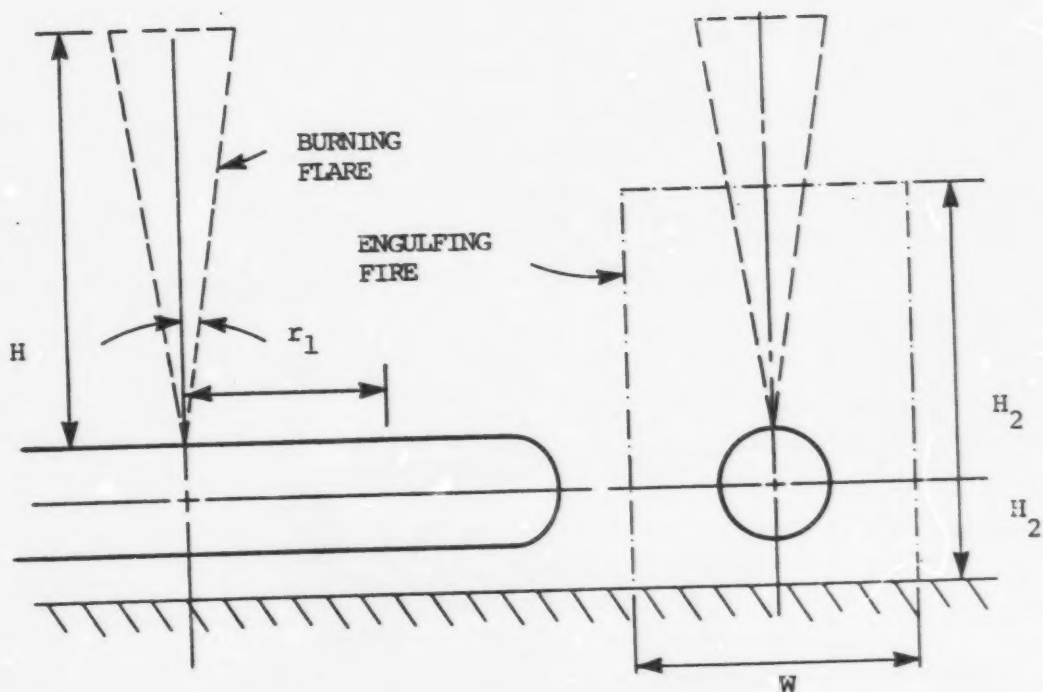


FIGURE 1-1 SKETCH SHOWING CONFIGURATION OF TANK WITH BURNING RELIEF VALVE FLARE

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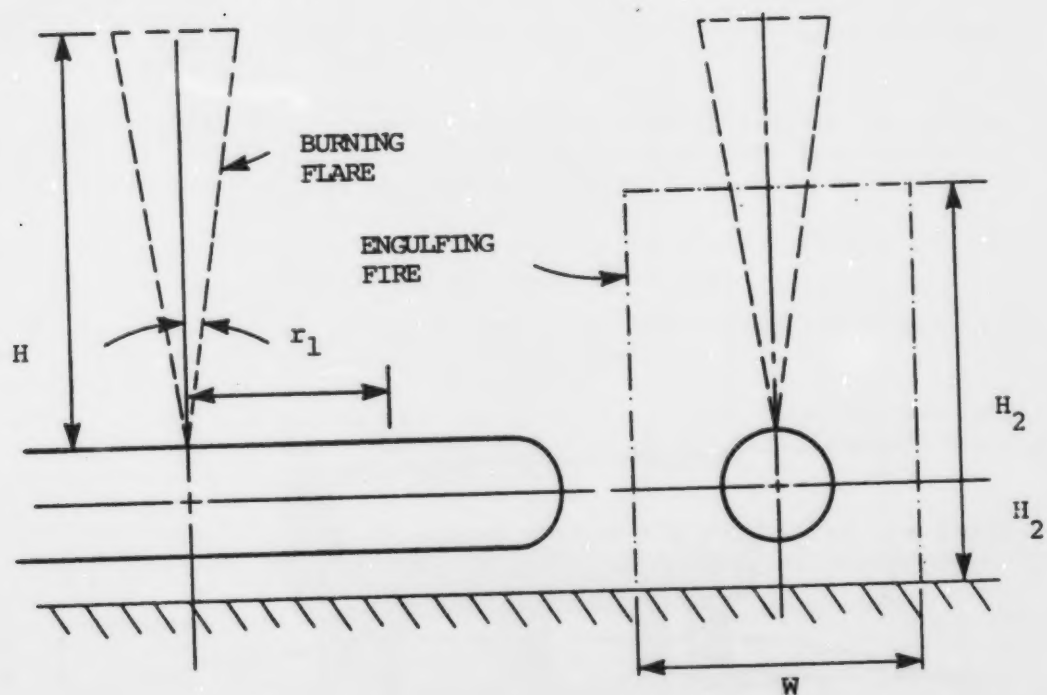


FIGURE 1-1 SKETCH SHOWING CONFIGURATION OF TANK WITH BURNING RELIEF VALVE FLARE

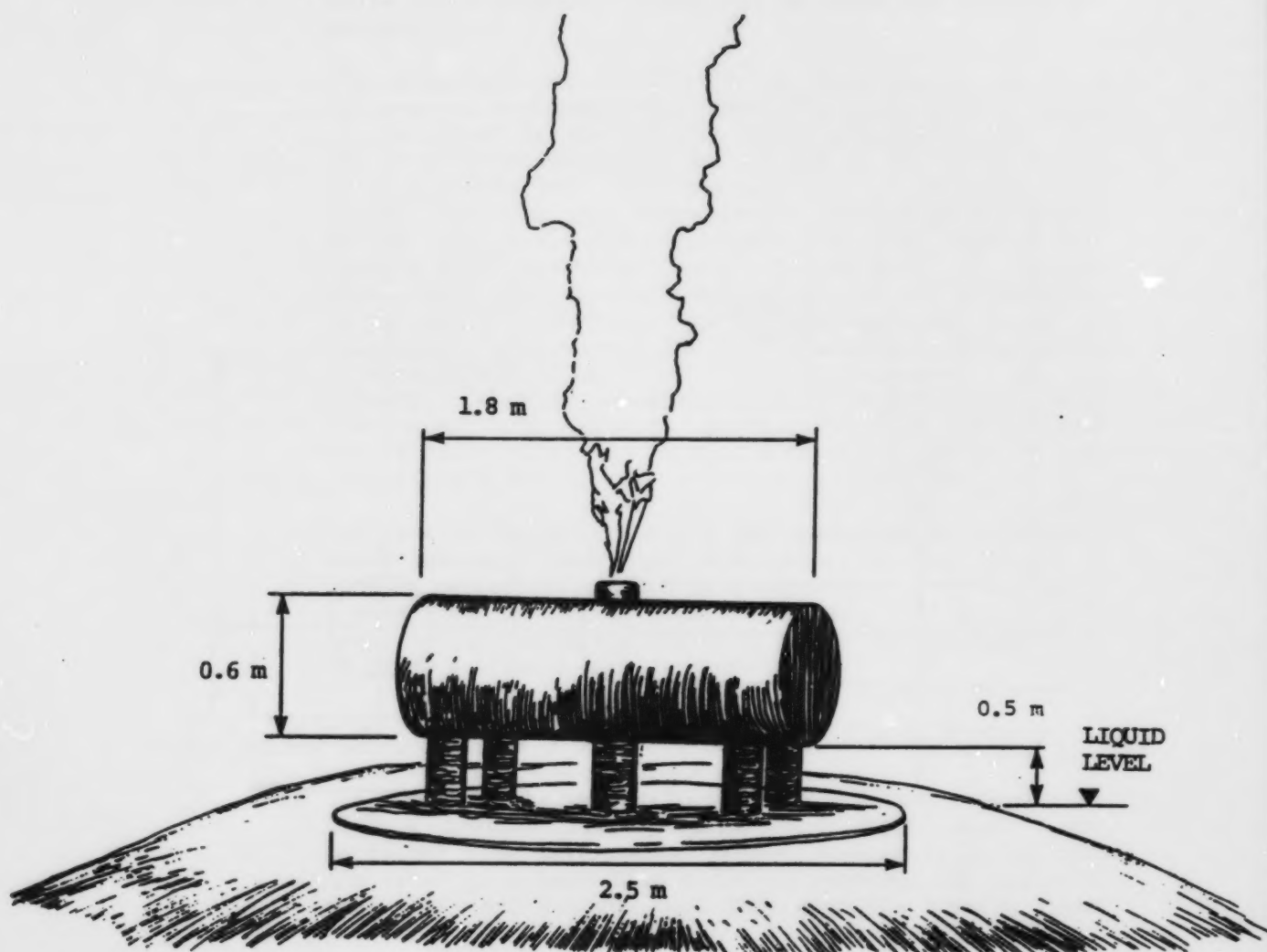


FIGURE 1-2 SKETCH OF SIMULATED TANK IN 2.5 M DIAMETER FIRE PAN

The overall objective of the fire test was, as stated earlier, to determine whether or not the burning relief valve flare is a significant heat source to the tank-car if the tank-car is already engulfed in fire. To meet this overall objective, the fire test had to meet the following detailed objectives.

- i) to determine the heat flux from a burning relief valve flare to the top dead centre (tdc) of a tank,
- ii) to determine the heat flux from an engulfing pool fire to the tdc of a tank,
- iii) to determine the heat flux to the tdc of a tank when both an engulfing pool fire and a burning flare are present,
- iv) to define the geometry and characteristics of the burning relief valve flare,
- v) to define the geometry and characteristics of an engulfing pool fire, and
- vi) to define the geometry and characterize an engulfing pool fire when a burning relief valve flare is present.

The following sections present the details of the tests that were performed to meet the above stated objectives.

1.3 SUMMARY

The fire tests reported in this document were performed indoors at the Fire Research Field Station, Division of Building Research, National Research Council Canada. The fire tests involved a simulated tank (approximately 1/5 linear scale of a rail tank-car) exposed to an engulfing pool fire fueled by JP-4. The tank was unprotected and filled partially with water. A simulated relief valve flare, fueled by propane, was also part of the fire tests.

During the test program several fire tests were conducted, including: three flare tests, one pool fire test, and two pool fire and flare tests.

The first flare and pool fire tests were conducted as trials to test the equipment and the experimental procedure. The first flare test was completely successful. The first pool fire test was intended to be a pool fire and flare test but unfortunately the high heat fluxes resulted in an electrical failure and as a result, the flare solenoid valve could not be opened, and the test

became a pool fire test only. The test was continued even though the flare was not present because the pool fire was sufficient to test the equipment and the experimental procedure. Upon completion of the pool fire test, it was found that the three total heat flux instruments mounted at the tank top-dead-centre had been destroyed sometime during the pool fire test. Therefore, at least part of the data from this test is considered questionable. Other than the three total flux meters, the remaining instruments survived and the test procedure was deemed adequate.

The total flux meters were replaced with more robust designs and two test sessions were conducted, each consisting of a flare test and a pool fire and flare test. The flare tests involved approximately a five minute flare burn with all instruments running. The pool/flare fire tests involved a sequence consisting of the pool fire startup, and maintained pool fire burn for approximately fifteen to twenty-five minutes, followed by a burn out. During the pool fire burn the flare was present two or three times for periods lasting three to five minutes with time gaps between the flare burns of three to five minutes. During the entire sequence, all the instrumentation was operating.

The most significant data obtained from the fire tests include: fire temperatures, tank wall temperatures, tank lading temperatures, total heat flux to the tank top-dead-centre (three locations), and radiant heat fluxes to remote targets. As well as the above, visual records of the fire tests were recorded on video tape and in still photographs.

Based on the results obtained from the fire tests, it appears that the presence of the burning relief valve flare has little or no effect on the tank when it is already engulfed in fire. This conclusion supports the results obtained from the mathematical model reported in Reference (1). However, the presence of the burning flare did have a significant effect on the geometry of the pool fire. It appears that the high velocity flare jet resulted in enhanced air entrainment and mixing in the pool fire which caused a taller fire. This stretching of the pool fire was clearly observed during the tests. The change in the fire geometry did not, however, have any dramatic effect on the radiant heat transfer to the remote targets (radiometers).

The results of the tests verify the assumption used to develop the tank-car thermal computer model which ignored the presence of the relief valve flare. It had been assumed that the engulfing pool fire attenuated the effects of the flare.

2.0 DESCRIPTION OF TESTS

As mentioned previously, the tests were performed at the Fire Research Field Station, Division of Building Research, National Research Council Canada. The tests were performed indoors where the fire could be protected from unwanted environmental effects such as wind.

This section presents the details of the test apparatus and instrumentation, and the experimental procedure.

2.1 APPARATUS AND INSTRUMENTATION

The test apparatus consisted basically of a simulated tank-car (approximately 1/5 scale) situated over a 2.5 m diameter pool fire. The simulated tank was filled with water for the tests and a pipe rising through the centre of the tank supplied propane from a remote storage tank for the simulated relief valve flare.

Figure 2-1 presents a sketch of the simulated tank. As the figure shows, the tank was approximately 1.8 m long by 0.61 m in diameter. The tank had flat ends with openings to ensure that the tank could not pressurize. A sleeve was located at the tank mid section so that a propane feed pipe could rise up through the tank. The propane feed line was located in this way so that the flare would appear to originate from the tank where a relief valve would normally be located.

The tank was supported by legs approximately 0.8 m above the ground (approximately 0.60 m above fuel surface). The pan containing the pool fire fuel was 2.5 m in diameter and had a .20 m hole in the centre for the propane feed line to pass through. A tube was welded to the pan to form a riser which would act as a radiation shield for the propane line and for the instrumentation wiring. When the tank was placed in the pan, the riser passed up through the tank sleeve. The pan has a lip height of .20 m. During the tests a false floor was created to make the top of the pan lip, the fuel surface, and the false floor approximately flush. This was done to eliminate edge effects which can significantly affect the pool fire.

As mentioned earlier, the flare was fueled by propane supplied from a remote storage tank. The propane line consisted of 51 mm pipe which lead from the storage tank and up through the pan riser and tank. In the riser the

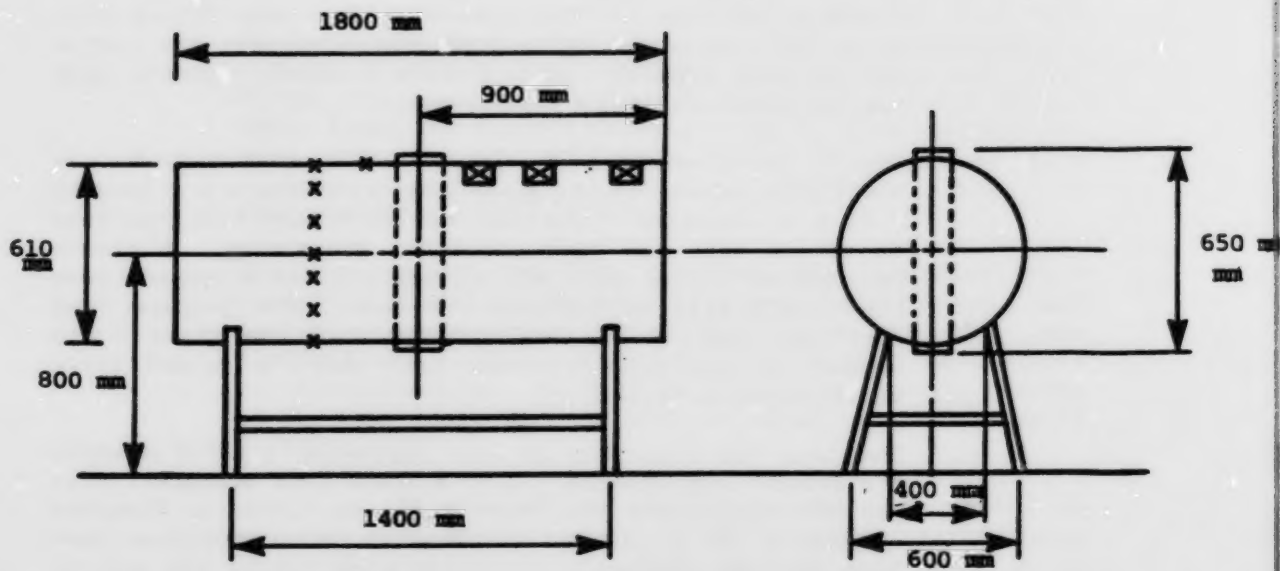


FIGURE 2-1 SIMULATED TANK-CAR USED IN FIRE TESTS

pipe was reduced to 19 mm where a 19 mm solenoid valve was located.

The solenoid valve had an effective port diameter of 15 mm. The line was designed for minimum pressure drop to ensure that there was enough pressure at the solenoid valve to result in choked flow through the valve. This was considered very important because it would result in a very high velocity jet for the flare which is typical of tank-car relief valve flares. A pressure transducer was located just upstream of the solenoid valve so that mass flow rates could be estimated.

The test instrumentation provided the following information:

- fire temperatures,
- flare temperatures,
- tank wall temperatures,
- radiant heat flux to remote targets,
- total heat flux to tank top dead centre,
- lading temperatures,
- propane supply pressure,
- JP-4 fuel level,
- fuel pan liquid level,
- entrained air dynamic pressure (for entrainment velocity), and
- entrained air temperature.

The tank was instrumented with heat flux meters, wall and lading thermocouples, and fire thermocouples. Figure 2-2 shows a sketch of the tank with instrument locations identified. The lading thermocouples were placed in a grid as shown in Figure 2-3.

As can be seen from Figure 2-2 the heat flux meters were located along the tank top-dead-centre at three different axial positions on one side of the tank. The flux meters were specially made for the test and the details of their design can be found in Appendix C. The wall thermocouples were located at the same locations as the flux meters except on the opposite side of the flare source, and at different circumferential locations (0, 30, 60, 90, 120, 150 and 180° from tdc) on one axial plane. Some fire thermocouples were located 10 cm above the tank surface at 0, 90 and 180° from the circumferential locations at the same axial plane as the tank wall thermocouples.

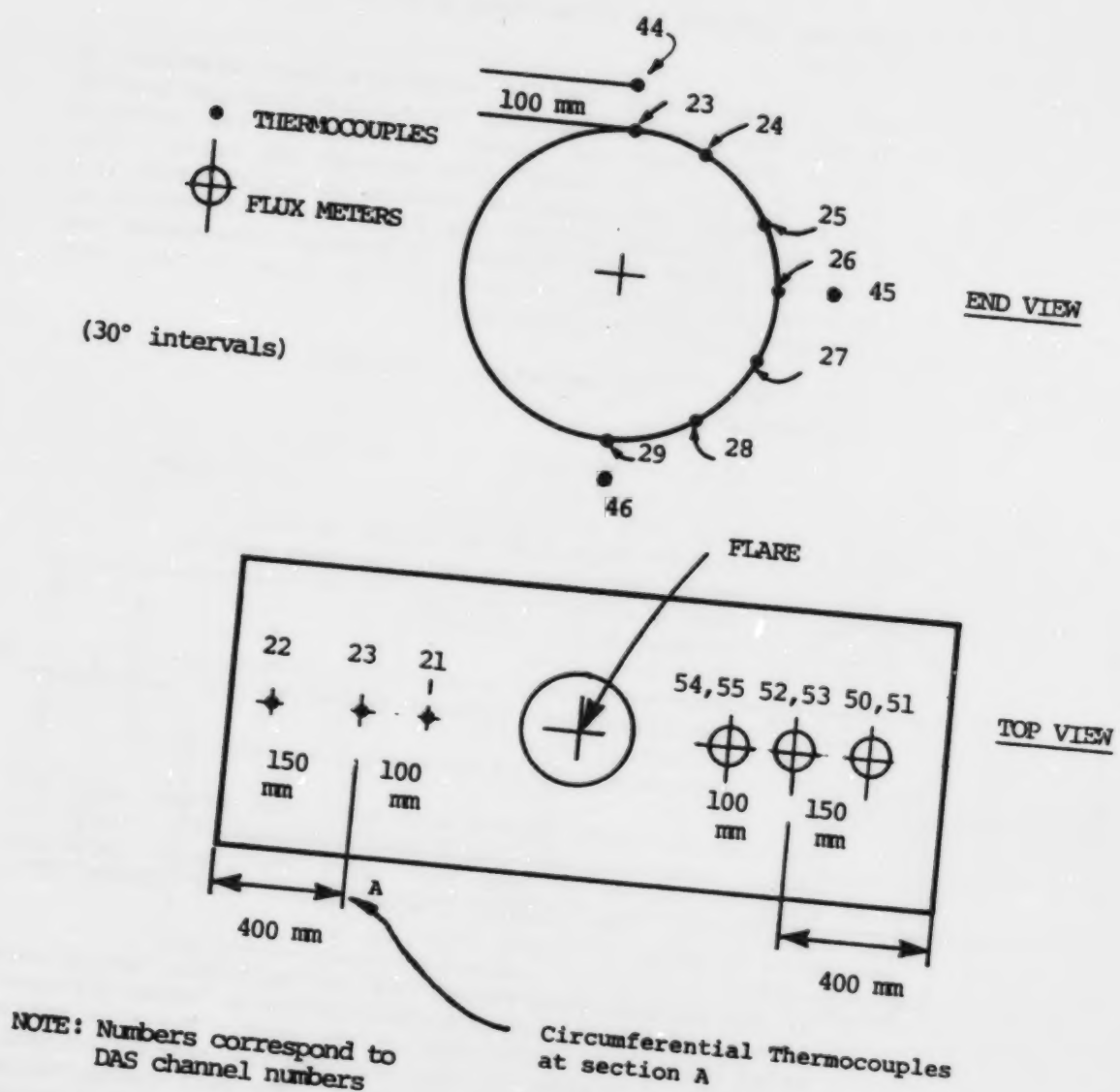


FIGURE 2-2 SKETCH OF TANK SHOWING INSTRUMENT PLACEMENT

NOTE Numbers indicate
channel numbers
on data acquisition
system

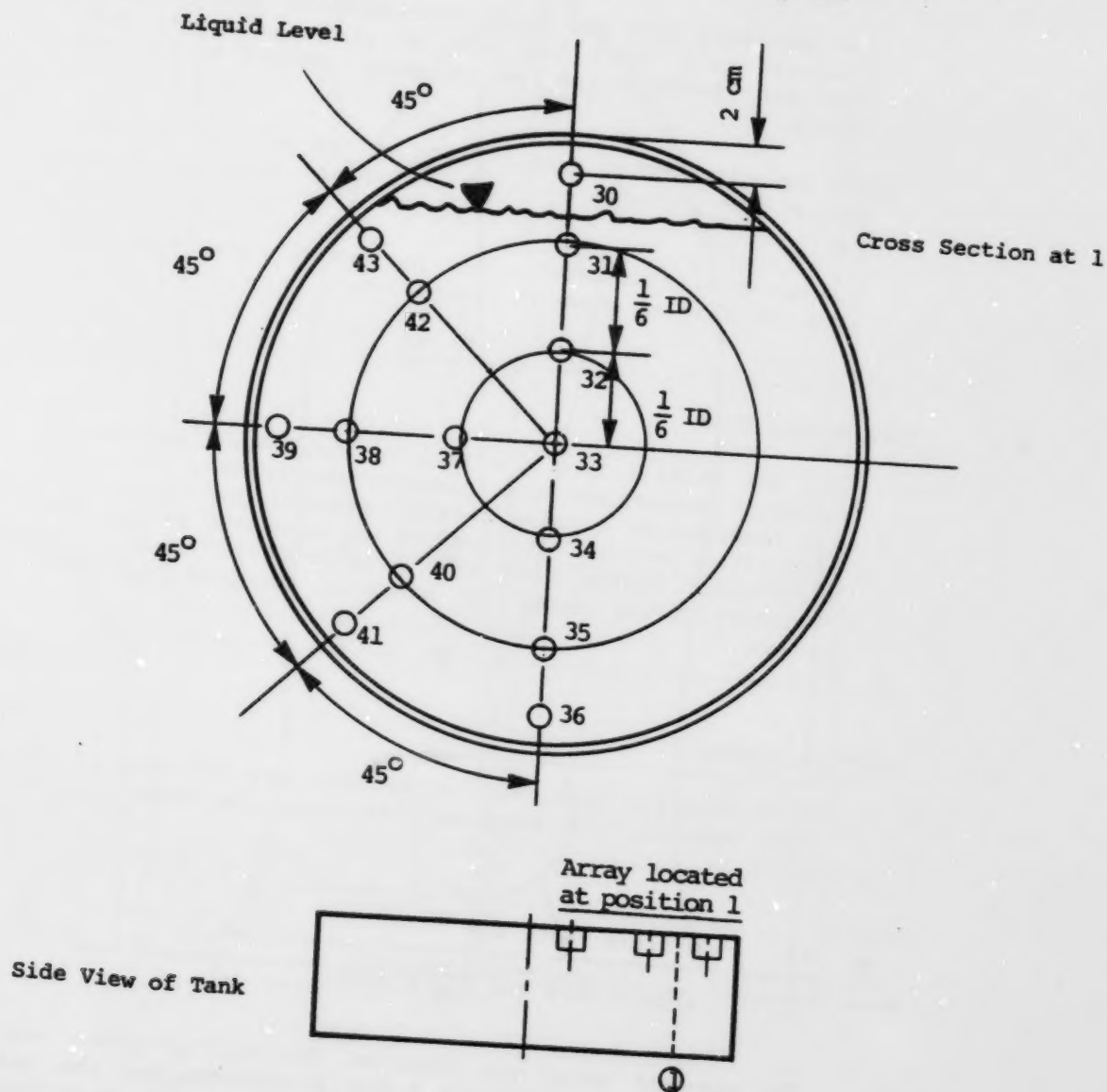


FIGURE 2-3 LADING THERMOCOUPLE GRID DETAILS

All of the thermocouple leads and the flux meter cooling lines were fed through a hole in the tank sleeve and fuel pan riser, down the riser and into a trench along the test hall floor.

The remaining fire and flare thermocouples were placed in a course grid above the tank as shown in Figure 2-4. Shielded thermocouples are clearly identified in the figure.

The velocity probes were located at the edge of the fire pan at one circumferential location, as shown in Figure 2-5.

The external radiometers were located at three distances from the fire as shown in Figure 2-6.

2.2 DATA ACQUISITION

All the signals from the various instruments except the velocity probes and some pressure gauges were collected and recorded by a multi channel computer controlled data acquisition system. Instruments not connected to the data acquisition system were either recorded on chart paper (velocity probe data) or manually recorded (pressure gauges).

2.3 TEST PROCEDURE

There were two basic test procedures, one for each of the test formats. As mentioned earlier, the test formats were;

- i) a flare test, and
- ii) a pool fire and flare test.

The pre-test setup was identical for both of these test formats. A description of the procedures for the two tests and the pre-test setup will now be described separately.

NOTE Numbers are channel numbers on data acquisition system

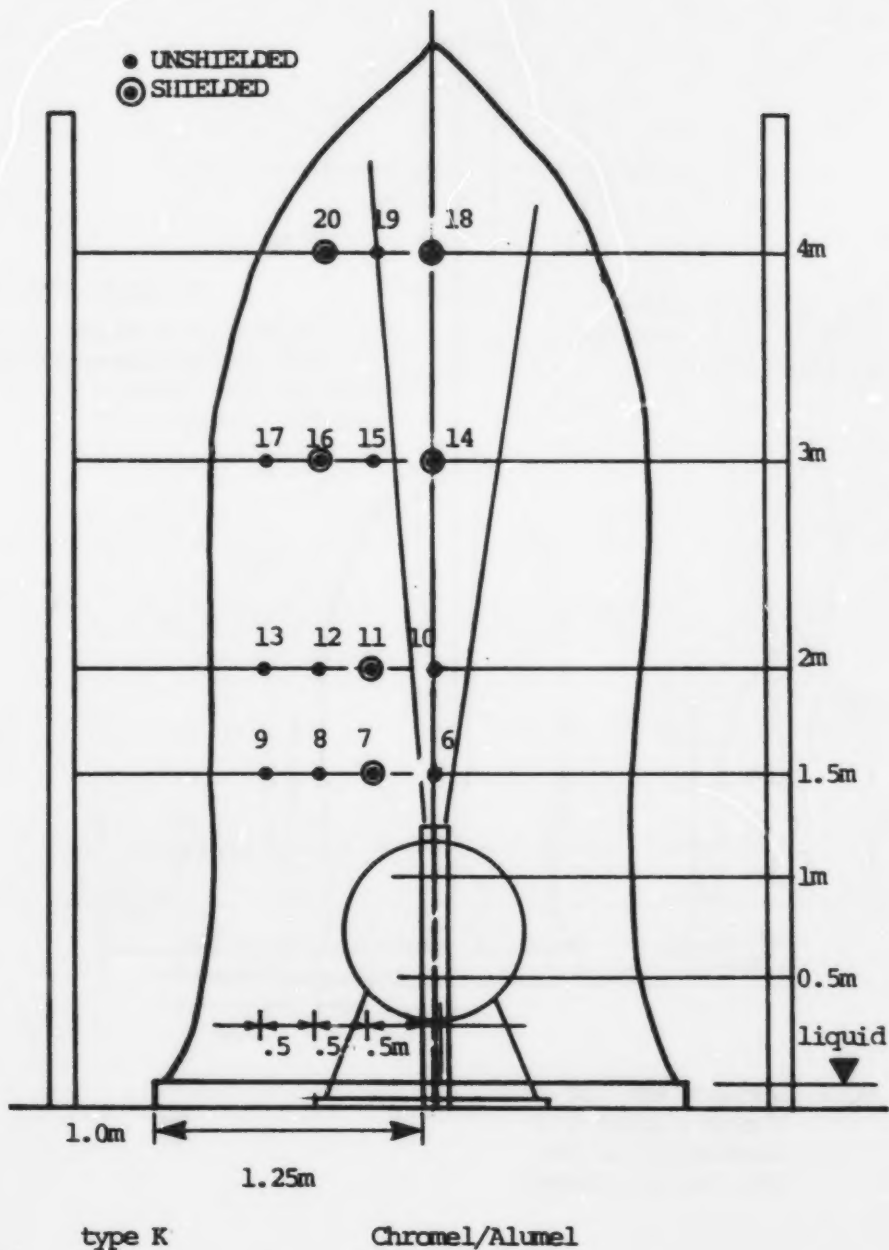


FIGURE 2-4 FIRE THERMOCOUPLE GRID DETAILS

- all radiometers faced towards the fire
- numbers correspond to DAS channel numbers

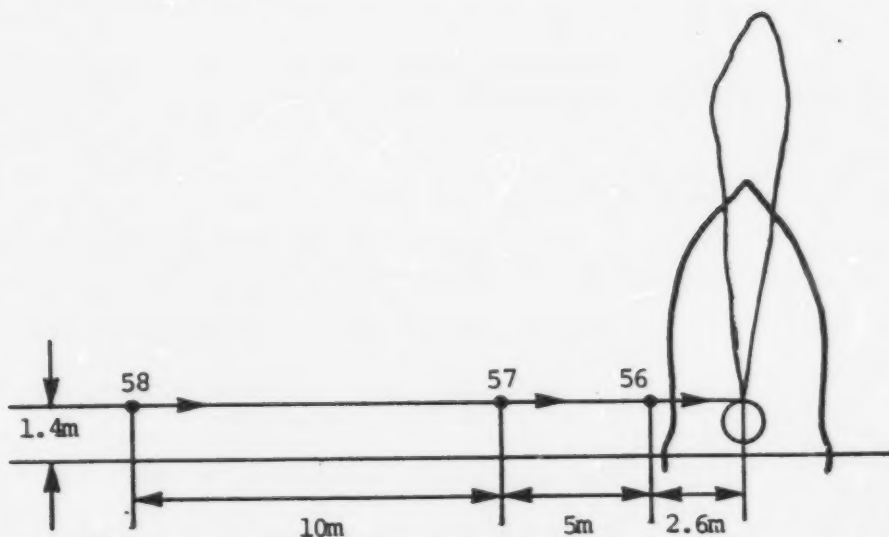


FIGURE 2-6 REMOTE RADIOMETER PLACEMENT DETAILS

Pre-Test Procedure:

As mentioned, the pre-test procedure was identical for all the tests performed. This procedure involved the following main tasks.

- i) The simulated tank was filled to approximately 80% capacity with water.
- ii) All instruments were checked for proper operation and support (i.e., power, cooling water flow, etc.).
- iii) The data logger was checked for operation and readied for start-up. All chart recorders were checked for operation and paper status.
- iv) Safety equipment was positioned.
- v) Personnel were briefed on their duties and positions.

Test Procedure (Flare Test):

The flare only test procedure was relatively simple and involved the following tasks.

- i) Data logger and chart recorders were started.
- ii) Propane feed line was pressurized and the leak flow at the tank was ignited.
- iii) The main supply was opened to start the flare.
- iv) The flare was maintained for 5 - 8 minutes.
- v) The flare was shut down by closing the main supply valve for the propane line. The data logger and instruments were shut down.

Test Procedure (Pool and Flare Test):

The pool fire and flare test procedure was slightly more involved than the simple flare test and involved the following tasks.

- i) Fuel pan was filled to within 4 cm of the fuel pan

lip with water. Fuel (JP4) was added to bring the level to 2 cm from the fuel pan lip.

- ii) The data logger and chart recorders were started.
- iii) The fuel was ignited.
- iv) The pool fire was maintained for 15 - 25 minutes (fuel supply was manually controlled to maintain the fuel level within the pan).
- v) During the pool fire burn, the flare was introduced for periods of 3 to 5 minutes, two or three times during the pool fire burn. Time between flare burns varied from 3 to 5 minutes.
- vi) After the 15 - 25 minute pool fire burn, the pool fire fuel supply was closed and the pool fire was allowed to burn itself out.
- vii) The data logger and chart recorders were shut down.

3.0 RESULTS

The fire test results have been summarized using seven different plots as follows:

- plot #1: Wall Temperature along tdc vs. Time
- plot #2: Wall Temperature around Circumference vs. Time
- plot #3: Total Heat Flux along tdc vs. Time
- plot #4: Remote Radiant Flux vs. Time
- plot #5: Fire Temperatures above Tank vs. Time
- plot #6: Fire Temperatures around Tank Circumference vs. Time
- plot #7: Lading Temperatures vs. Time

The channel numbers (C_D) given in the plots, correspond to the instruments shown in Section 2.1.

The measured entrained air dynamic pressures have not been summarized from the chart records.

The raw data from all the tests, including the entrained air dynamic pressure records, is not included in this report. Anyone wishing this data should contact the Transportation Development Centre or the authors.

All of the test data will not be presented in this section. Instead, one set of results from each of the two test formats (flare only, pool and flare) will be presented. The results from the remaining tests are presented in Appendix A.

All of the flare tests gave very repeatable results. However, because of the instrument failures in the first pool fire test, flare test #1 had different total flux meters than tests #2 and #3. Therefore the results from test #3 will be presented here.

Of the pool/flare tests performed, test #2 had the most steady fire conditions, and therefore this test will be discussed in detail.

3.1 FLARE TEST #3

Flare test #3 involved a 6 minute flare burn. The results obtained from the test are summarized in Figures 3-1 to 3-7. It should be noted that the vertical scales chosen for these plots are the same as those used for the plots of the pool/flare results. This was done to facilitate direct comparison between the test results.

Figure 3-1 presents the measured wall temperatures at the tank tdc. As can be seen from the figure, there is a gradual increase in the wall temperatures during the flare burn.

Figure 3-2 presents the measured wall temperatures at different circumferential locations around the tank. As one would expect, the wall locations closer to the tank bottom do not see the flare, and therefore there is no temperature increase in these areas. Gradual temperature increases are seen for the wall locations nearer the tank top, where there is a direct line of sight from the tank wall to the flare.

Figure 3-3 presents the measured total heat flux to the tank tdc. As can be seen from the plots, the heat flux is very steady during the burn. The total measured heat flux was in the order of $4,000 \text{ W/m}^2$, with of course, some variation between the inboard and outboard flux meters.

Figure 3-4 presents the measured remote radiant fluxes. As one would expect, the closest flux meter sensed the highest radiant flux, and this was approximately $3,000 \text{ W/m}^2$. This flux compares well with the total flux reading of $4,000 \text{ W/m}^2$ (note that for the case of the flare test, the total flux meters would be sensing almost 100% radiant heat transfer).

Figure 3-5 presents the measured flare temperatures. As can be seen from the plot the flare centre-line temperatures are in the range of $1000 - 1100^\circ\text{C}$. Note that thermocouples for channels 14 and 18 (along flare centre-line) were shielded.

Figure 3-6 presents the measured temperatures 10 cm above the tank surface at three circumferential positions. As can be seen, the temperatures of the top thermocouple increased the greatest due to its position relative to the flare. It is very likely that the sensed temperatures were due entirely to radiant transfer from the flare and not due to air temperatures in the thermocouple vicinity.

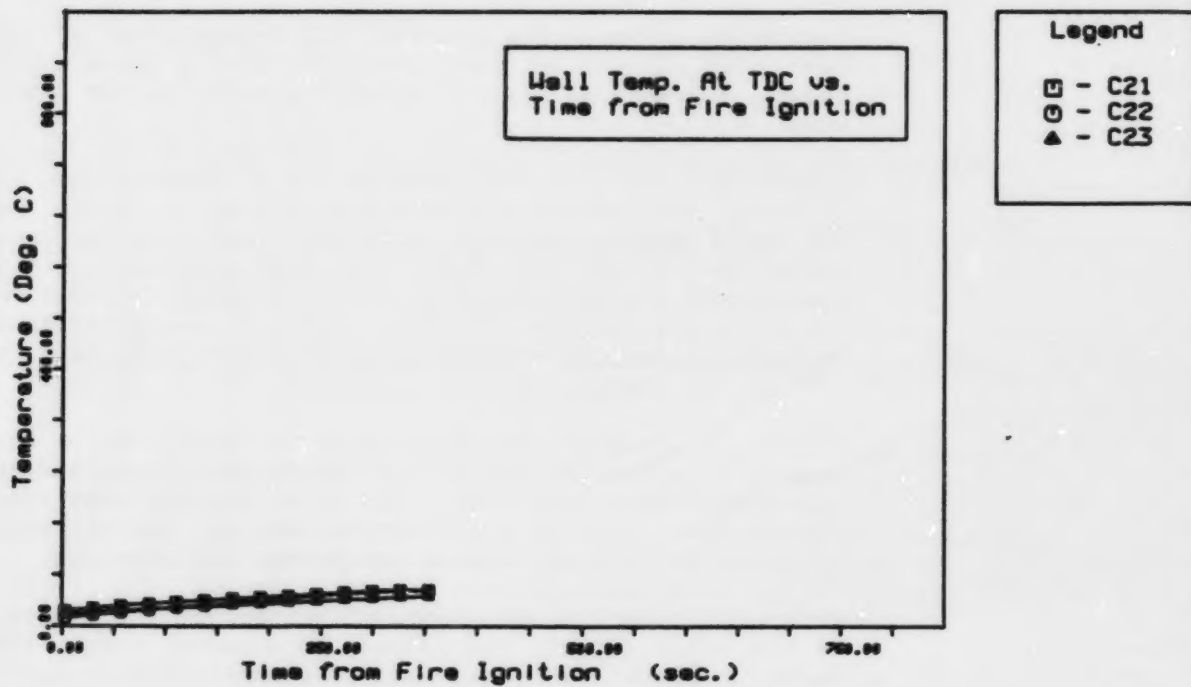


FIGURE 3-1 MEASURED WALL TEMPERATURES AT TANK TDC FOR
FLARE TEST #3

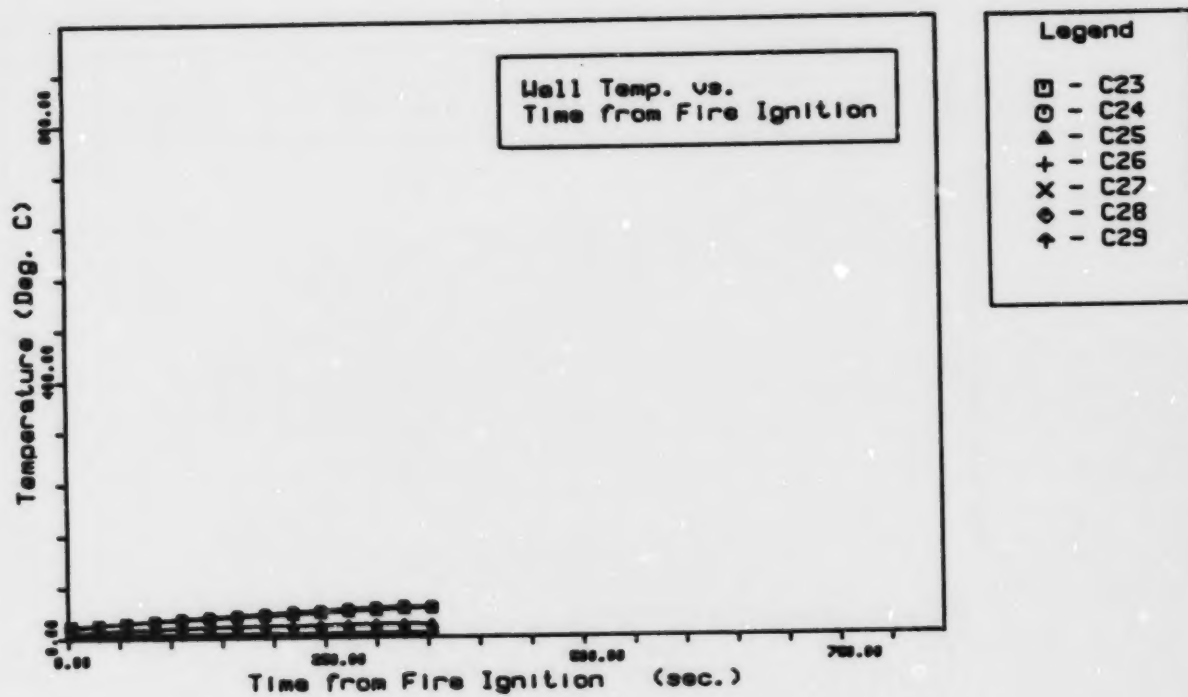


FIGURE 3-2 MEASURED WALL TEMPERATURES AROUND TANK CIRCUMFERENCE
FOR FLARE TEST #3

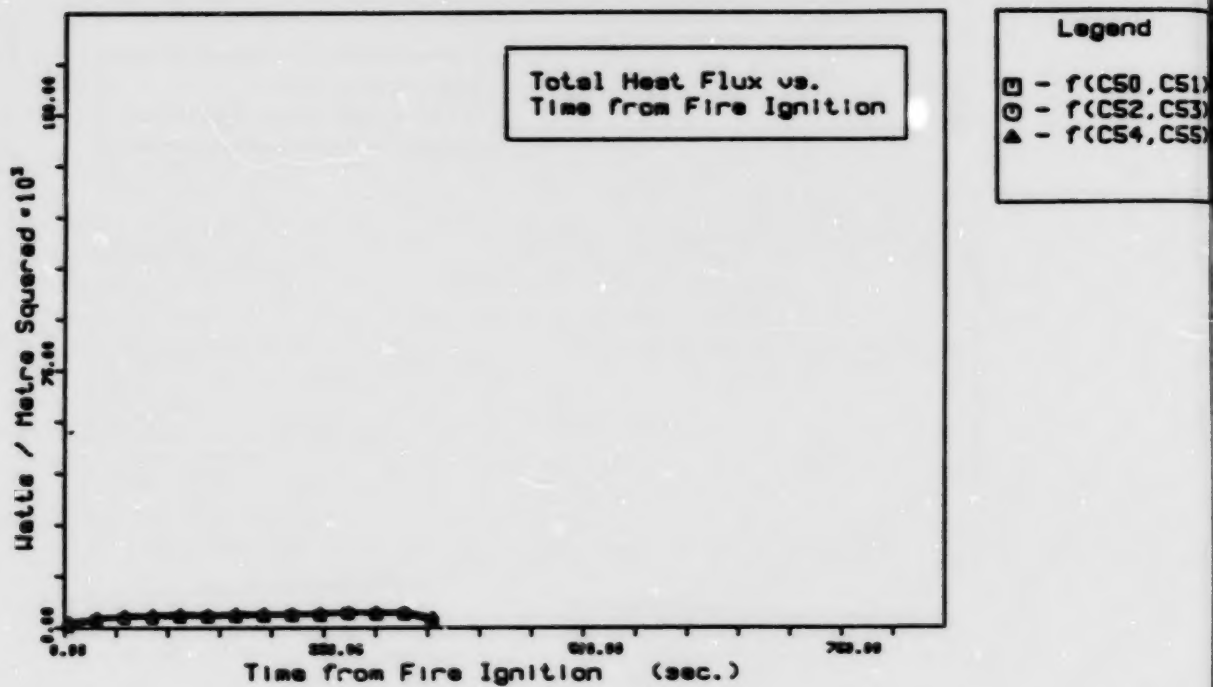


FIGURE 3-3 MEASURED TOTAL HEAT FLUX TO THE TANK TDC FOR FLARE TEST #3

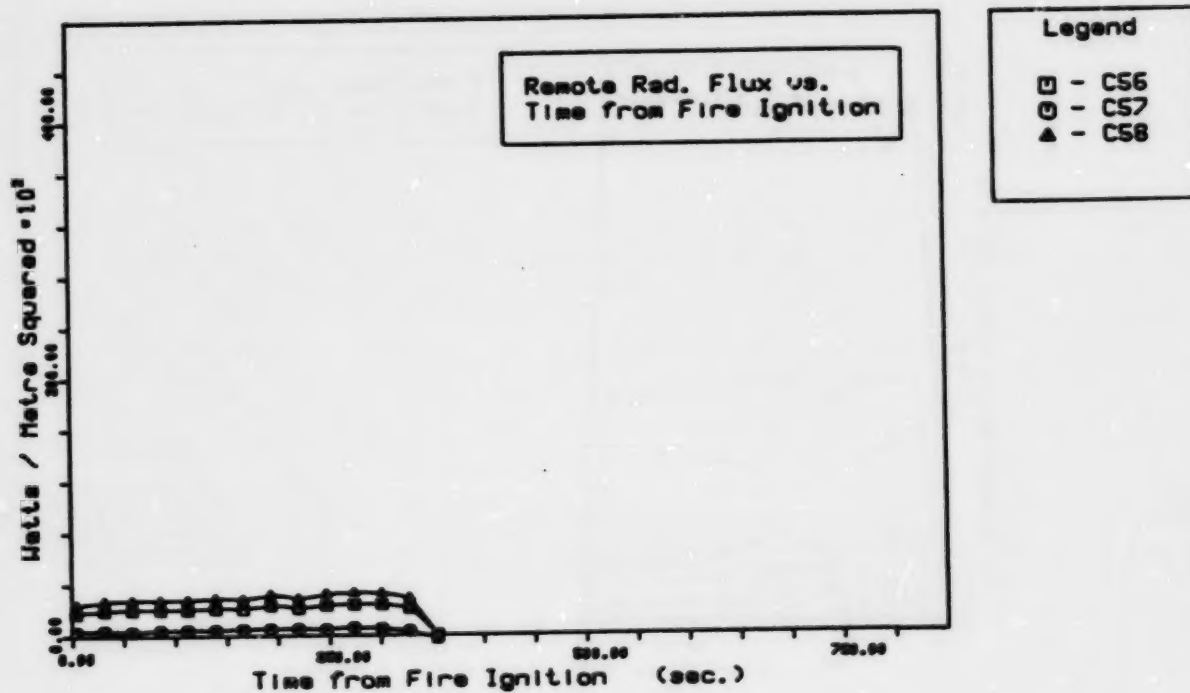


FIGURE 3-4 MEASURED REMOTE RADIANT HEAT FLUXES FOR FLARE TEST #3

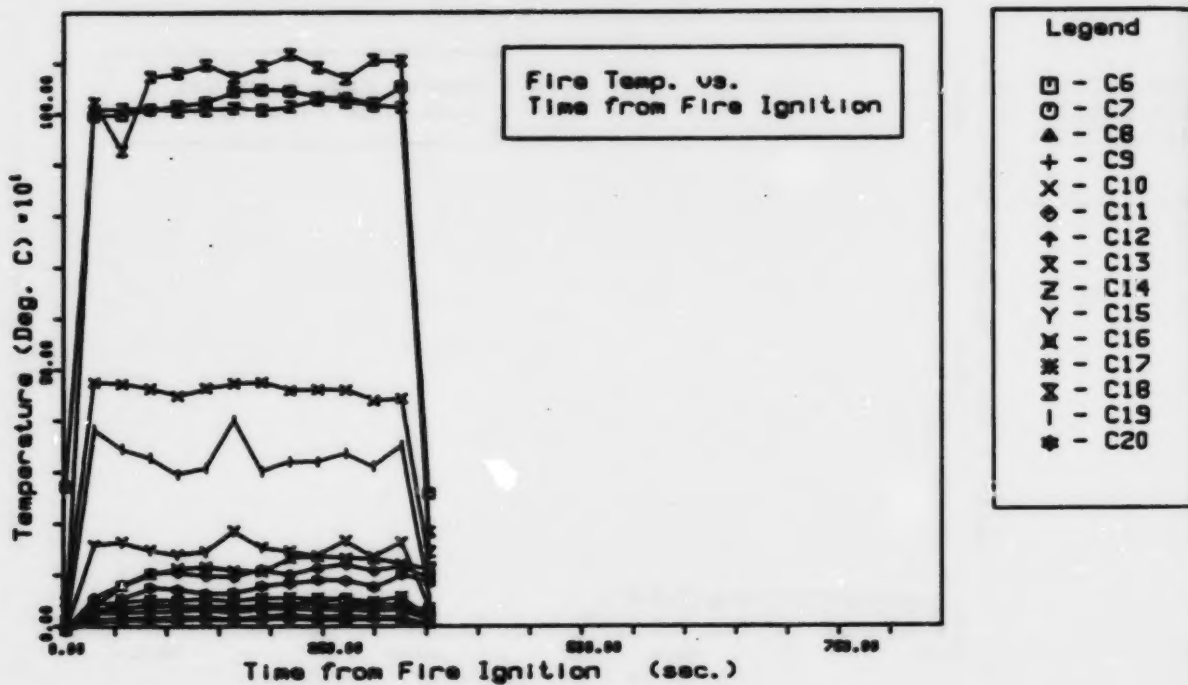


FIGURE 3-5 MEASURED FLARE TEMPERATURES FOR FLARE TEST #3

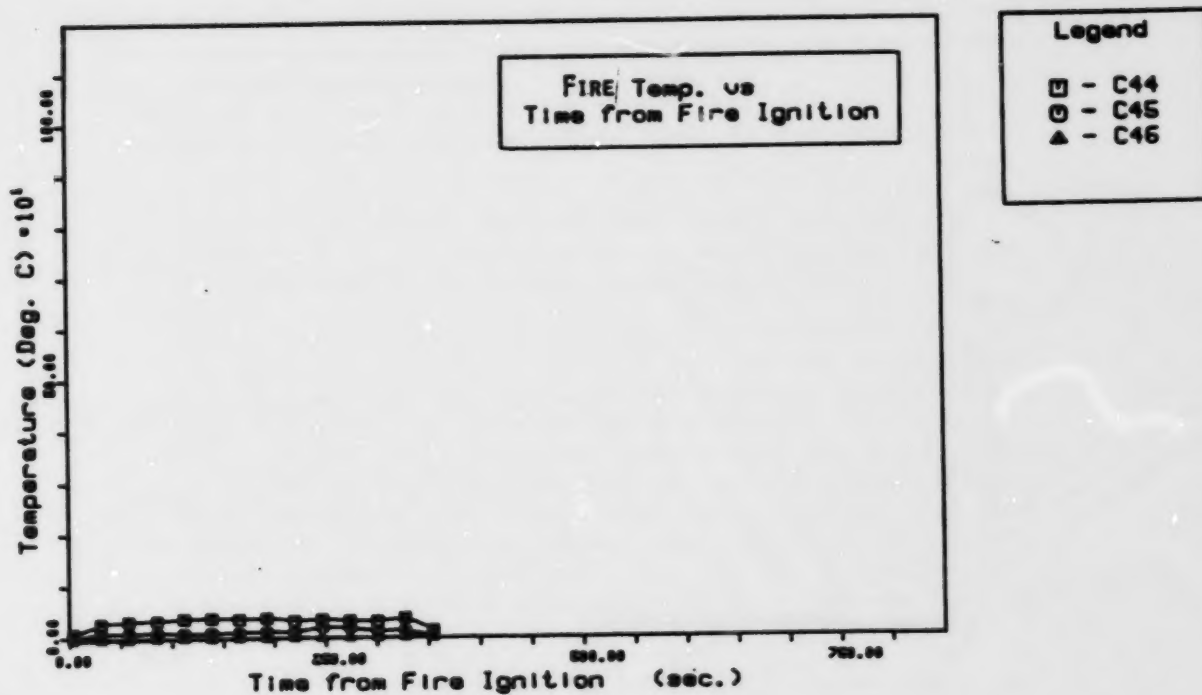


FIGURE 3-6 MEASURED TEMPERATURES 10 CM ABOVE TANK SURFACE FOR FLARE TEST #3

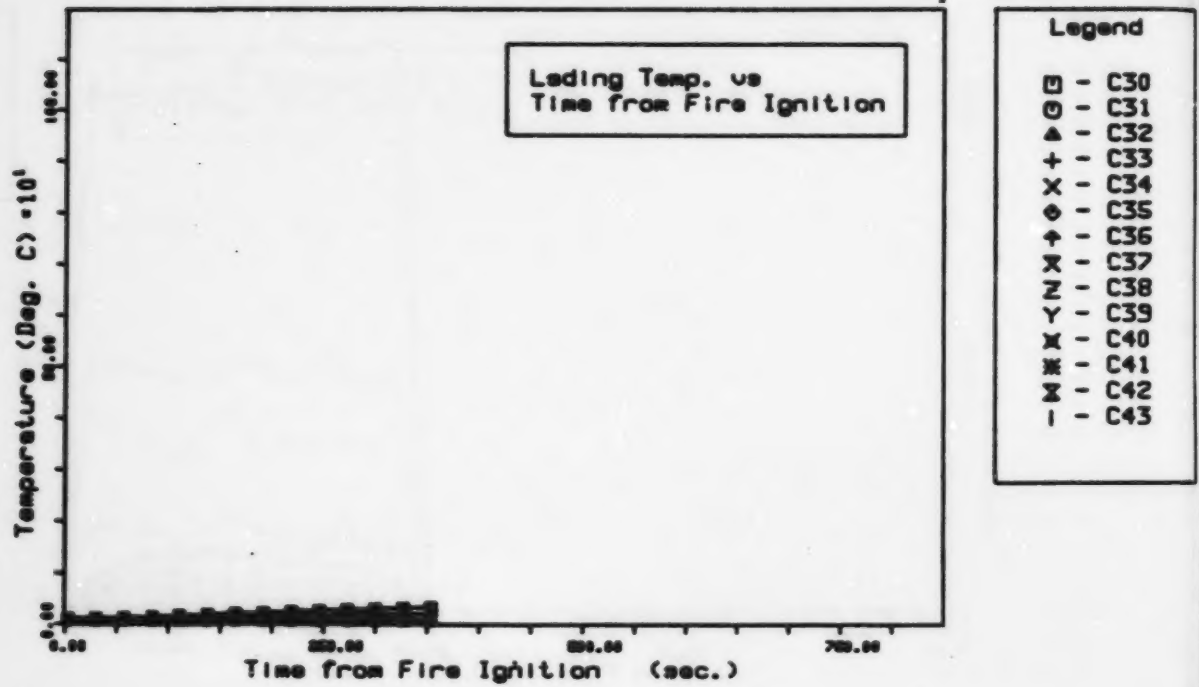


FIGURE 3-7 MEASURED LADING TEMPERATURES FOR FLARE TEST #3

Figure 3-7 presents the measured lading temperatures for flare test #3. As can be seen from the figure, only the thermocouples in the vapour space sensed any temperature increase during the short flare burn.

3.2 POOL/FLARE TEST #2

Pool Fire/Flare test #2 involved a 14.5 minute pool fire burn during which two flare burns were conducted. The timing of the flare burns is indicated on the plotted data about to be introduced.

The results of the pool/flare test #2 are presented in Figures 3-8 to 3-14.

The vertical scales used in these plots are identical to those used in the presentation of the flare test #3 data. This was done to facilitate direct comparisons.

Figure 3-8 presents the measured wall temperatures along the tank tdc for pool/flare test #2. As can be seen from the figure, the wall temperatures increased rapidly until they reached near equilibrium conditions. As expected, the inboard wall locations experienced the most rapid increases in wall temperatures because of their position with respect to the fire centre (surfaces near the fire centre will experience higher heat fluxes because their field of view is filled with fire and the resulting mean beam length is higher than for a surface near the edge of the fire).

Figure 3-9 presents the measured wall temperatures at different circumferential positions on the tank wall. As expected, the wall locations nearest the tank top experienced the highest temperatures. Those wall areas below the liquid level in the tank experienced the lowest temperatures.

Figure 3-10 presents the measured total heat flux at three locations along the tank tdc. As can be seen from the figure there was an initial period where the heat fluxes increased rapidly, followed by a period of near steady heat flux. As expected, the inboard heat flux meters registered the highest heat flux. This is due, of course, to the fact that the inboard flux meters see the largest volume of flame. The steady heat flux readings give an indication of the very steady fire conditions, and also indicate the negligible effects resulting when the flare

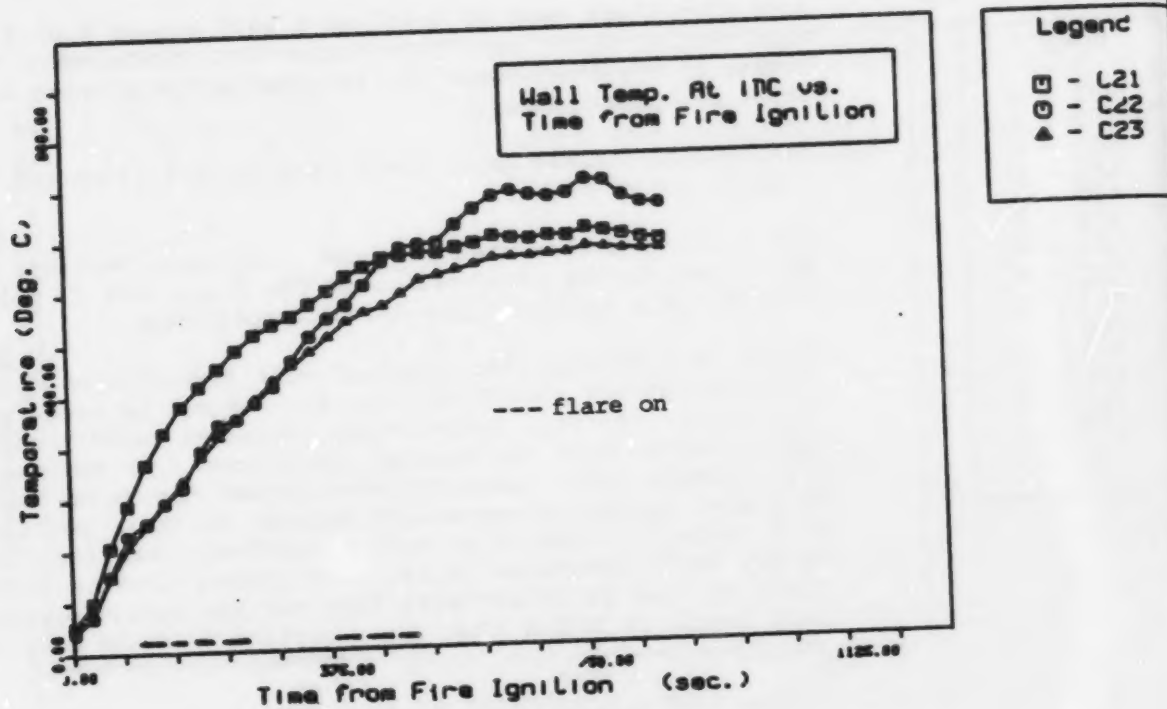


FIGURE 3-8 MEASURED WALL TEMPERATURES AT TANK TDC FOR POOL/FLARE TEST #2

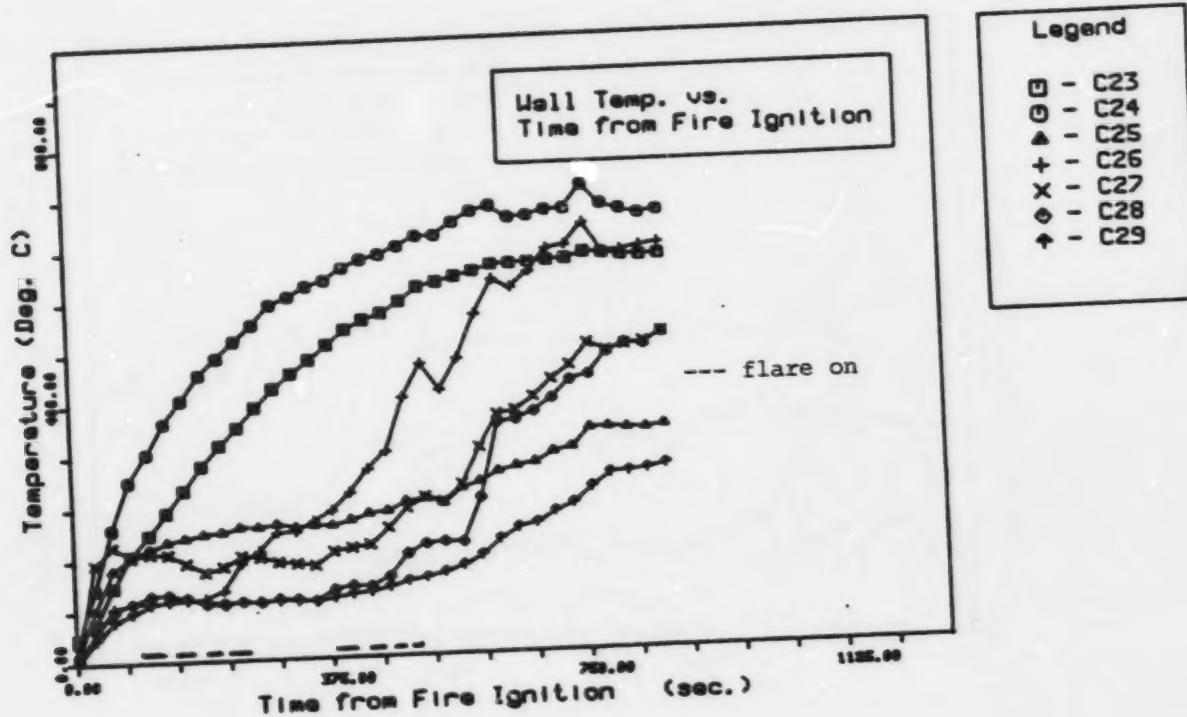


FIGURE 3-9 MEASURED WALL TEMPERATURES AROUND TANK CIRCUMFERENCE
FOR POOL/FLARE TEST #2

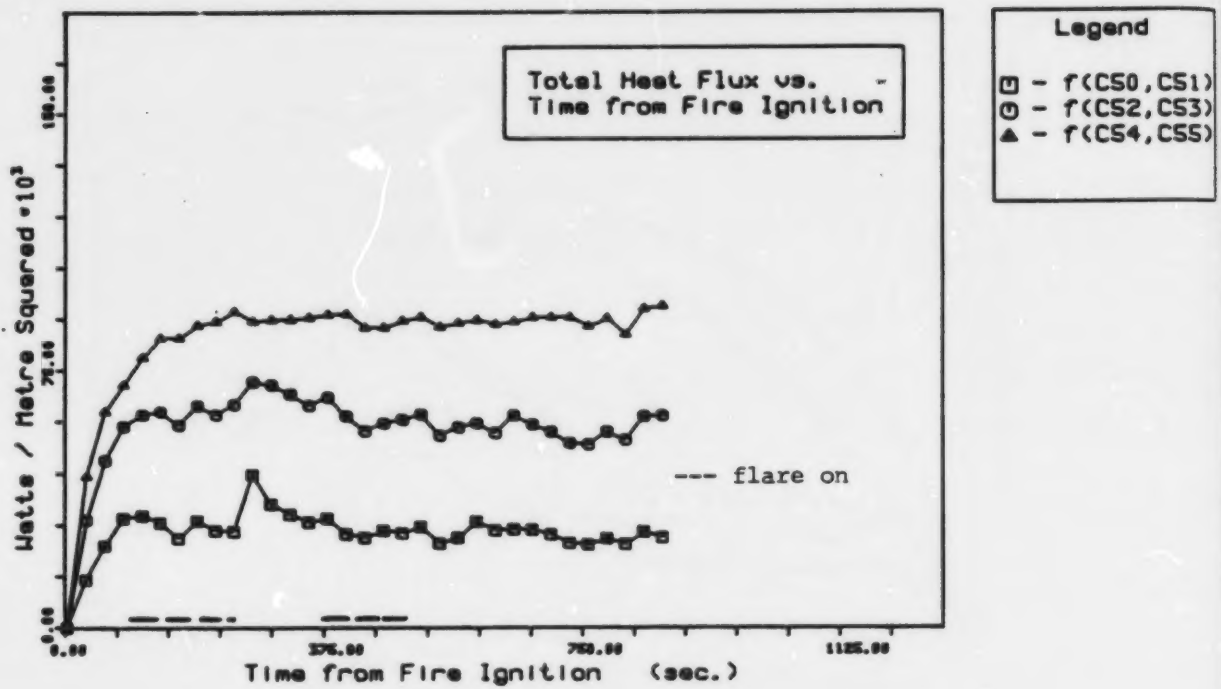


FIGURE 3-10 MEASURED TOTAL HEAT FLUX AT TANK TDC FOR POOL/FLARE TEST #2

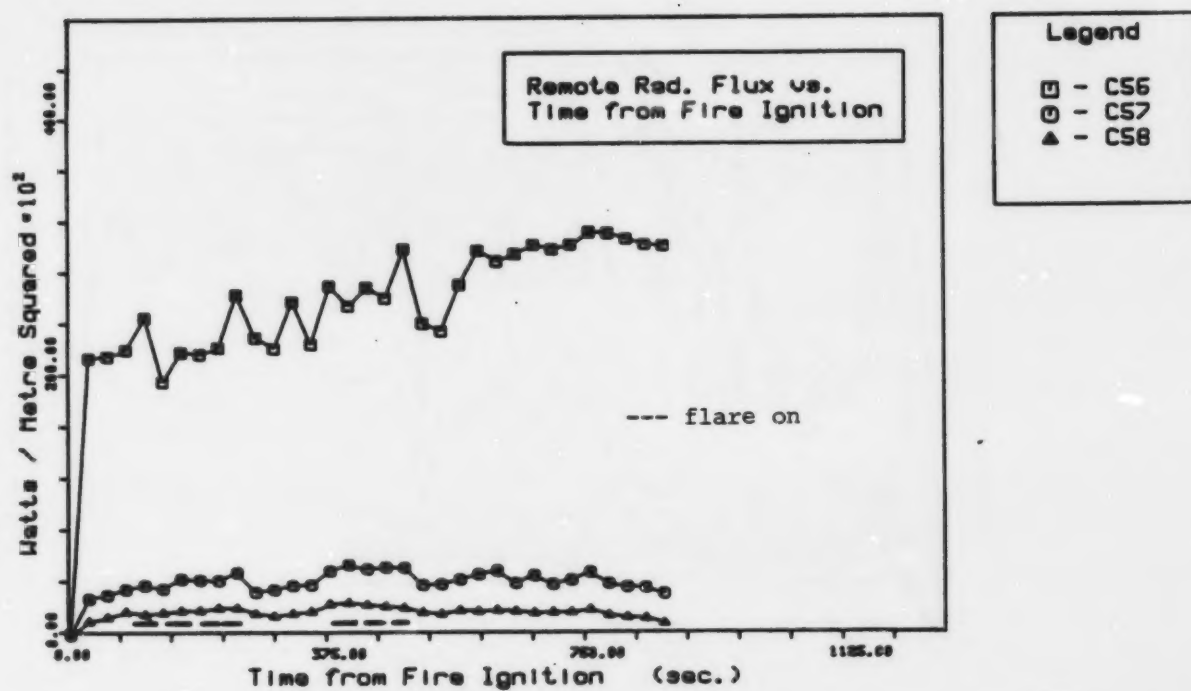


FIGURE 3-11 MEASURED REMOTE RADIANT HEAT FLUX FOR POOL/FLARE TEST #2

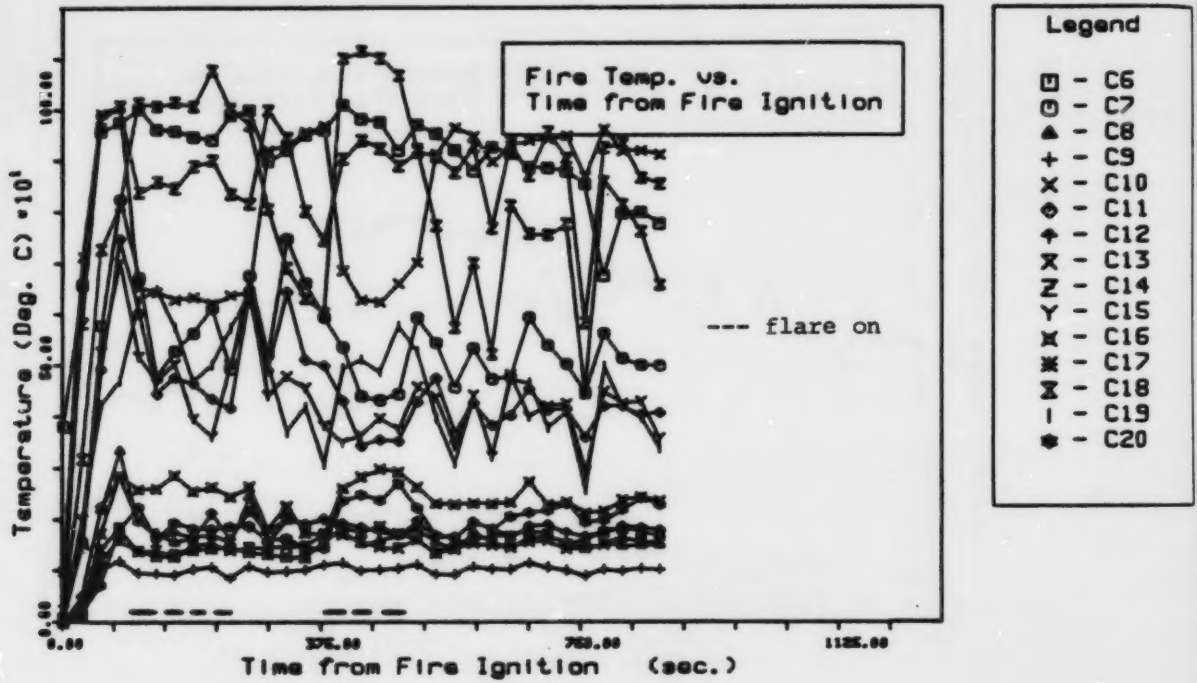


FIGURE 3-12 MEASURED FIRE TEMPERATURES FOR POOL/FLARE TEST #2

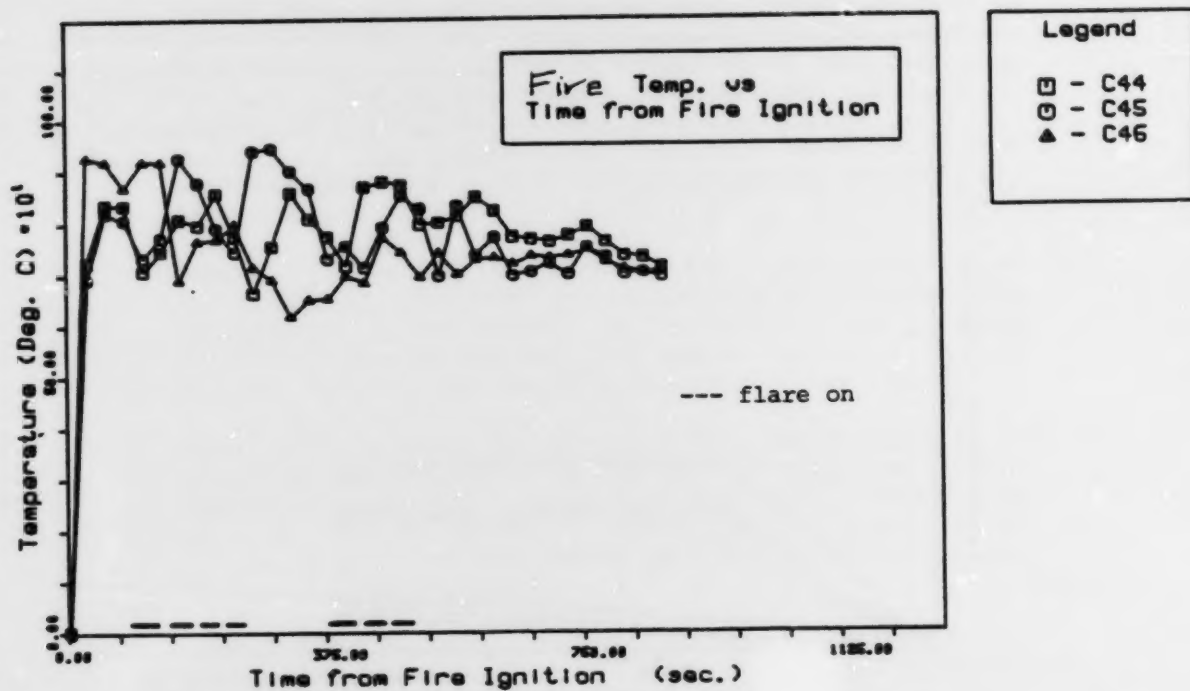


FIGURE 3-13 MEASURED TEMPERATURES 10 CM ABOVE TANK SURFACE FOR
POOL/FLARE TEST #2

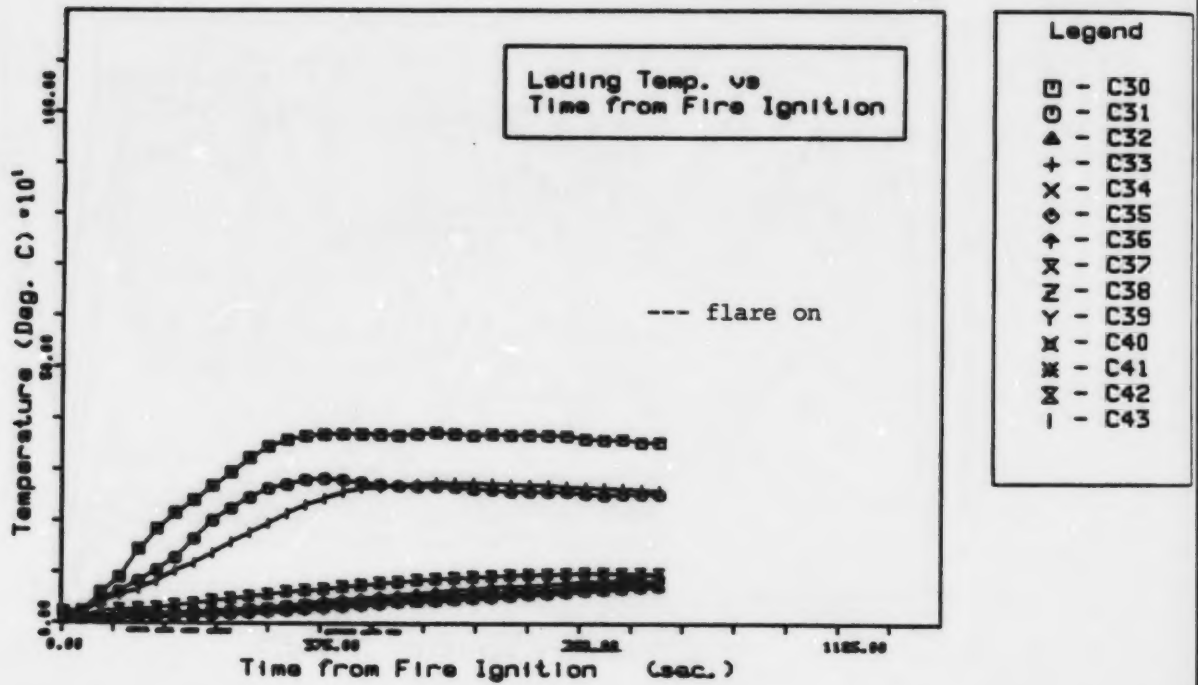


FIGURE 3-14 MEASURED LADING TEMPERATURE FOR POOL/FLARE TEST #2

is present. The effects of the flare will be discussed further later.

Figure 3-11 presents the measured radiant fluxes at the remote radiometers. As expected, the radiometer nearest the fire sensed the highest flux. The flux measured by the radiometer mounted closest to the fire does not appear to show any effects of the flare. However, there does appear to be some correlation between slight increases in flux and the presence of the flare in the two remaining radiometers. This is easily explained by the fact that the fire geometry does change somewhat when the flare is present (the fire is taller, possibly due to increased mixing and air entrainment resulting from the high momentum flare jet). This will be discussed further in a later section.

Figure 3-12 presents the measured fire temperatures above the tank. As seen from the figure, the fire centre-line temperatures ranged between 700 and 1000°C. The presence of the flare can be seen by sudden increases in the measured temperatures directly above the flare source.

Figure 3-13 presents the measured fire temperatures 10 cm above the tank surface. As can be seen from the figure, the fire temperatures near the tank wall ranged from approximately 700 to 900°C. There does not appear to be any correlation between these measured temperatures and the presence of the flare.

Figure 3-14 presents the measured lading temperatures during pool/flare test #2. As can be seen from the figure, the thermocouples mounted in the vapour space sensed the highest temperatures. The thermocouples mounted in the lading sensed much lower temperatures. The presence of the flare does not appear to affect the lading temperatures in any way.

4.0 ANALYSIS AND DISCUSSION

This section analyses the results of the present fire tests and discusses these results with regard to the thermal response of a real tank-car exposed to similar conditions.

4.1 FIRE GEOMETRY AND TEMPERATURES

The fire tests were conducted indoors so that uncontrollable effects such as cross-winds could be eliminated. The following sections describe the observed geometries and recorded temperatures of the different fire tests conducted.

i) Flare Only

In total, three flare tests were performed to measure the resulting effects on the simulated tank. The measured flare temperatures and the observed flare geometries were very similar for the three tests, and therefore the following discussion will exclude any reference to the actual test number.

The simulated flare was a typical turbulent diffusion flame with a visible length of approximately 6 - 7½ m. The flare supply pressure was adequate to result in choked flow at the flare source and therefore the flow velocities were representative of real tank-car relief valve flows.

Because the supply pressure was roughly 1/10 that experienced in a real tank-car, the mass flow through the simulated valve was roughly 1/10 that experienced in the TDC fifth-scale fire tests.

One of the objectives of the present study was to relate the findings obtained from the simulated pool/flare tests to the case of a real tank-car in a fire environment. To do this, it was necessary to determine the scale effects between the present test and real tank-cars. As well, it was desirable to relate the results from the present tests to the TDC fifth scale fire tests conducted at Suffield (3).

Before the scaling calculations are presented, the following facts should be noted. The present study involved a fire environment isolated from cross-winds. This makes the present test rather idealistic in that the

radiant heat transfer from a burning flare to a tank-car will be significantly affected by cross-winds because the geometrical view factors will be changed by a bending of the flare. These effects have been eliminated from the present test so that the problem could be reduced to its simplest form.

Therefore, the calculations about to be presented apply to the idealized case of a fire isolated from cross-winds, and the resulting conclusions should not be considered valid for an actual fire where cross-winds may be important. Further study is necessary if the effects of cross-winds are to be examined.

The following pages present the scaling calculations for the simulated pool/flare fire test. Similar calculations have been performed for full and fifth-scale tank-cars with assumed fire conditions similar to those experienced in the present test (i.e., no cross-winds assumed present).

The mass flow through the relief valve (vapour flow only) can be calculated from the following relation for choked nozzle flow.

$$\dot{m} = \eta A_t [P_o \rho_o \gamma \left(\frac{2}{\gamma + 1} \right)^{\frac{\gamma + 1}{\gamma - 1}} a]^{1/2} \quad (1)$$

where

$$a = (\gamma + 1)/(\gamma - 1) \quad (2)$$

η = valve efficiency ($\approx .85$),

A_t = throat area $\approx 1.8 \times 10^{-4} \text{ m}^2$ in this test,

P_o = stagnation pressure = 172 kPa for this test,

ρ_o = source density = 3.35 kg/s in this test,

γ = ratio of specific heat (1.2 for propane)

With the above parameters, the estimated mass flow for the simulated flare is 0.075 kg/s.

From the above mass flow, the total energy flow can be calculated by multiplying the mass flow rate by the heat

of combustion for propane (50340 kW/kg). For the simulated flare the total energy flow is approximately 4×10^3 kW.

An order of magnitude estimate for the jet velocity can be obtained from the relation for the flow velocity at Mach 1.0 (i.e., choked flow at the minimum area section in the simulated relief valve). This relation is as shown below:

$$V = \sqrt{\frac{2\gamma}{\gamma + 1} RT_0} \quad (3)$$

where,

R = gas constant = $188.7 \text{ m}^2/\text{s}^2\text{K}$

T_0 = source stagnation temperature (K)

For the simulated flare this jet velocity was 237 m/s.

Two dimensionless parameters, the flame Reynolds number and the Richardson ratio are important in relating free turbulent diffusion flames. The Reynolds number is an indication of the turbulence level in the flame, and the Richardson ratio is an indication of the importance of buoyancy in the flame. Further discussion of the importance of these parameters can be found in References (4) and (5). In the present application the above ratios are calculated from the following approximate relations.

$$R_{eL} = 4 \times 10^7 \dot{m}_0 / L \quad (4)$$

$$R_{iL} = \frac{10 L^3}{\dot{m}_0 U_s} \quad (5)$$

$$R_{iS} = \frac{10 D_s^3}{\dot{m}_0 U_s} \quad (6)$$

where,

$\dot{m}_O$ = propane mass flow (kg/s)

L = visible flame length (m)

U_s = momentum mean gas speed at exit (m/s)

D_s = effective jet diameter = $D_O (\rho_O / \rho_\infty)^{1/2}$

For the case of the simulated flare the calculated values of the above parameters are:

$$R_{eL} = 4.3 \times 10^5$$

$$R_{iL} = 200$$

$$R_{iS} = 8 \times 10^{-6}$$

It is important in the present study that the Reynolds number for the flare be large so that the turbulence in the flame is similar to actual flares, and also that the Richardson ratio be of the same order of magnitude as for the real tank-car valve flare. It will be seen later that these basic requirements have been met.

With the Reynolds and Richardson numbers known, it is possible to estimate the radiation losses from the flares. Reference (4) presents the radiation loss in terms of the total energy flow $\dot{m}\Delta h_c$. For the simulated flare this loss is approximately $0.15^C \times 4 \times 10^3 = 600$ kW.

As an order of magnitude estimate of the flame radiosity, this radiant loss can be divided by the flare surface area. Of course, this estimate of the radiosity is not strictly correct because the radiation from the flare is not isotropic, but for the present purposes this estimate should be adequate.

In the present case the flare areas were calculated assuming the flare is a cone with a total spread angle of 18° . This spread angle was assumed to be the same for all tank scales and only the flare length was varied. For the simulated flare the radiosity was calculated to be 24.3

kW/m^2 . If the flame were radiating at 1100°C then the above radiosity would result if the flame had an effective gray emissivity of 0.12, which is reasonable.

The remaining factor that needs to be calculated to obtain the radiant flux to the tank is the view factor. A view factor for this geometry was calculated in Reference (1). The view factor will stay approximately the same for the different scales because of the geometrical similarity. The view factor F_{ij} assumed is 0.088. This view factor when multiplied by the flare radiosity gives an order of magnitude estimate of the flux to the tank top-dead-centre. For the simulated flare case this flux is 2100 W/m^2 . This estimate agrees well with the measured flux of 4500 W/m^2 , considering the fact that the present analysis is order of magnitude only.

The above calculations have been performed for the fifth-scale tests conducted at Suffield and for a full-scale tank. The results of these calculations are summarized in Table 4-1.

The results of the calculations show that the fluxes measured in the present study are of reasonable scale and therefore the conclusions drawn from the present study can be directly applied to the case of tank-cars in environments free of significant cross-winds. However, it should be noted that the cross-winds that bend the flare significantly will increase the flame to tank view factor and hence the radiant flux. Reference (6) presents an analysis to predict such effects.

ii) Pool/Flare Fire Test

In total, three pool fire tests were performed and two of these included flare burns during the pool fire. As stated previously, the first pool fire test did not include a flare burn because of an electrical failure that made the flare solenoid valve inoperable.

During the pool fire portion of the burns, the tank was generally totally engulfed in fire, except for its ends. Based on visual observation only, the fire appeared to be very sooty and turbulent. The visible flame height ranged from approximately 5 to 7 m. The fire diameter tapered from its based of 2.5 m to a minimum of approximately 1.6 m just above the tank level.

CASE	SOURCE PRESSURE	SOURCE TEMP.	SOURCE DENSITY	VALVE AREA	JET VELOCITY	$\dot{m}$	$\dot{m} h_c$	R_{fs}	L	R_{eL}	Q_R/A	FLARE TO TANK TDC FLUX G
present test	kPa	°C	kg/m ³	m ²	m/s	kg/s	kW		m		kW/m ²	W/m ²
	172	0	3.35	1.8×10^{-4}	237	0.075	4×10^3	8×10^{-6}	7	4×10^5	24.3	2100
fifth scale tests	1864	55	30.1	2.7×10^{-4}	260	1.11	6×10^4	3×10^{-5}	23	2×10^6	34.6	3000
full scale tank	1864	55	30.1	50.6×10^{-4}	260	20.8	1×10^6	1×10^{-4}	81	1×10^7	60.4	5300
NOTE: the above figures apply only for a flare isolated from cross-wind effects view factor $F_{ij} = 0.088$ for all scales												

TABLE 4-1 FLARE TO TANK TDC RADIATION CALCULATION SUMMARY FOR THREE DIFFERENT SCALES

As a result of the flame taper, the tank ends could occasionally be seen free of the fire. Because of the lack of cross-wind currents, the pool fires were upright in most cases. However, during the pool/flare test #2, there appeared to be some fire leaning due to stray currents in the burn hall.

The temperatures recorded during the pool fire only portions of the tests showed, as expected, the fire temperatures increased towards the centre of the fire. Also, as expected, the fire temperatures decreased with increasing height above the tank. The fire thermocouples mounted near the tank surfaces at different circumferential locations showed that the fire temperatures at the bottom of the tank were generally higher than those at the top of the tank.

However, there were large fluctuations in the flame temperatures due to the large scale turbulence, and these fluctuations make spacial resolution of fire temperatures very difficult without the aid of statistical analysis. It must be kept in mind that the present discussion is only based on cursory analysis of the plotted results.

When the flare was present during the pool fire, the flame taper was increased and the visible flame height was significantly increased. This stretching of the pool fire was likely caused by the high velocity flare jet. The visible flame height reached a maximum of approximately 15 m.

As with the pool fire alone, the pool/flare combination had a shape which varied along its height. At the base the fire diameter was approximately 2.5 m and this quickly tapered to approximately 1.4 m just above the tank. Above the tank, the pool/flare fire appeared as a column of fire of near constant diameter.

The measured fire temperatures clearly show the presence of the flare. The temperatures measured directly above the flare source show significant increases when the flare is present. However, the overall flame temperatures did not appear to change dramatically from those when the flare was not present. Once again, the above observations are based on cursory analysis of the plotted results.

4.2 TANK WALL TEMPERATURES

The tank wall temperatures were measured because they are an indicator of the thermal response of the tank/lading system, and therefore can aid in determining the significance of the burning relief valve flare.

In the flare only tests, the wall temperatures did not increase very rapidly. The most significant temperature increase took place near the top of the tank. This happened for two reasons,

- i) because the flare to tank radiant exchange factors are highest for the tank top, and
- ii) because of vapour wetted wall effects.

When the pool fire was present the wall temperatures increased very rapidly.

As in all the fire tests previously conducted, the wall temperatures are highest at the top of the tank where the tank inner surface is exposed to vapour. Wall areas wetted by liquid were generally much cooler, as expected.

Results from previously conducted fire tests involving propane filled tanks showed that the liquid wetted wall temperatures followed the liquid temperatures very closely. This, however, was not the case for the present fire test. The results of pool and flare test #2 showed that the liquid water temperatures approached 100°C (boiling temperature of water at 1 atm). However, the liquid wetted wall temperatures reached temperatures above 300°C, or 200°C above the liquid temperatures. This temperature excess is an order of magnitude higher than those recorded in the propane filled tank tests. This large temperature excess is explained by the fact that the boiling curve for water is significantly different than that for propane.

When the flare was introduced during a pool fire burn, there were no significant changes in the response of the tank wall. From this, it can be concluded that the presence of the relief valve flare is not significant when the tank is already engulfed in fire.

4.3 FIRE TO TANK HEAT FLUX

Because of the relatively large fire scale, the flame to tank heat flux is primarily due to thermal radiation. The pool fire was very sooty, and therefore it radiated nearly as a black body that surrounds the tank. The flare, on the other hand does not radiate as a black body but rather as a selective radiator because of the fact that the radiation is due primarily to CO_2 , H_2O and soot content of the flame. In addition, the geometrical view factor from the flare to the tank surface is relatively small.

Section 4.1 presented an order of magnitude analysis of the flare to tank radiant exchange. The following is an order of magnitude analysis of the pool fire to tank radiant transfer. The following analysis is based on the results of pool/flare fire test #2.

In pool/flare test #2 the measured wall temperatures at the simulated tank top-dead-centre reached an equilibrium at approximately 660°C . Based on a simple heat balance on the tank wall, the mean flame radiating temperature can be estimated. Such an analysis renders a flame radiating temperature of 832°C .

This calculation is shown below:

At wall equilibrium,

$$(\text{fire heat in}) = (\text{heat from wall to lading}) \quad (7)$$

Assuming that at the wall temperatures measured, the heat transfer is primarily due to thermal radiation, and assuming the surface emissivities of the wall inner and outer surface are the same, then the following applies:

$$T_f^4 - T_w^4 = T_w^4 - T_L^4 \quad (8)$$

where,

T_f = fire temperature,

T_w = wall temperature, and

T_L = lading temperature.

Therefore,

$$T_f^4 - 973^4 = 973^4 - 373^4 \quad (9)$$

or $T_f = 1105 \text{ K}$
 $= 832^\circ\text{C}$

The mean radiating flame temperature determined in this way agrees well with the average flame temperature measured around the tank. The average temperature measured by the three fire thermocouples mounted 10 cm from the tank surface was approximately 790°C .

Based on the above flame temperature of 832°C , a maximum potential radiant flux can be calculated from:

$$\begin{aligned} \frac{Q}{A} &= \sigma T_f^4 \quad (10) \\ &= 5.67 \times 10^{-8} \times 1105^4 \\ &= 84800 \text{ W/m}^2 \end{aligned}$$

This calculated flux agrees to within 6% of the total flux (radiant and convective) of approximately $90,000 \text{ W/m}^2$ measured at the inboard flux meter mounted in the tank wall at tdc.

The total measured heat flux to the tank did not change when the flare was introduced. There are two basic reasons for this:

- i) The radiant heat transfer to the tank when only the flare was present was only 5% of the flux measured when only the pool fire was present, and
- ii) because the pool fire acts as an absorbing intervening medium between the flare and the

tank, and as a result, the flare heat flux is attenuated.

The above two effects combine to result in a negligible wall heat flux being attributed to the flare. Based on this, it can be concluded for a large pool fire isolated from cross-winds, the presence of the flare is not significant in relation to the total heat flux to the tank.

4.4 FIRE TO REMOTE TARGET HEAT FLUX

The remote target heat fluxes were measured because they give an indication of how the pool/flare fire system may affect neighboring tanks or structures.

For the flare only tests, the measured fluxes at the remote stations were in the order of 2000 W/m^2 . The flux dropped as the distance from the flare to the remote flux meter was increased. This, of course, is due to a reduction in the radiant exchange view factors as the distance is increased.

For the pool fire tests, the remote flux readings were much higher (25000 W/m^2 for closest radiometer). The radiometer furthest from the fire sensed the lowest heat flux.

When the flare was introduced during the pool fire burn there was no measured increase in radiant flux to the closest radiometer. This is because the field of view of this radiometer was almost filled with the pool fire.

However, the two radiometers furthest away appeared to measure slight increases in incident flux when the flare was present. This is easily explained by the fact that the fire size is significantly increased when the flare is present, and therefore the remote radiometers saw more fire.

Based on the above statement, it can be concluded that remote targets (such as neighboring tanks) may receive higher heat fluxes when a burning relief valve flare is present. The amount of incident flux on a remote target will depend on the distance between the target and the fire source.

5.0 CONCLUSIONS AND RECOMMENDATIONS

The following conclusions were made based on the results of the present fire tests. The conclusions apply strictly for the case where cross-wind effects are negligible. Some of the conclusions apply for full sized tank-cars, however, scaling effects must be accounted for when extrapolating the results of this test to full-scale conditions. The basic conclusions of the tests are as follows:

- i) The heat flux from a burning flare by itself, to the tank, is very low in comparison to the heat flux from an engulfing fire. However if the flux from the flare is maintained by itself for a long enough period, the effects on the tank lading system could be significant.
- ii) The effects of a burning relief valve flare on a tank, when the tank is already engulfed in fire appear to be negligible. This is because of the attenuating effects of the engulfing fire, and because of the geometric view factors applicable for the flare/tank surface radiant exchange.
- iii) The presence of the burning relief valve flare has a significant affect on the geometry of the pool fire. The high velocity flare jet results in a stretching of the pool fire. The stretching causes the fire to thin out and elongate.
- iv) The presence of the relief valve flare, and its effect on the pool fire geometry appears to affect the radiant heat flux to remote targets. This is likely due to the increased size of overall fire.

The results of the present fire test indicate that under ideal conditions (no cross-winds) the effects of the burning relief valve flare are small. However further study is required before the importance of the burning flare are fully understood. The following are recommendations for future work.

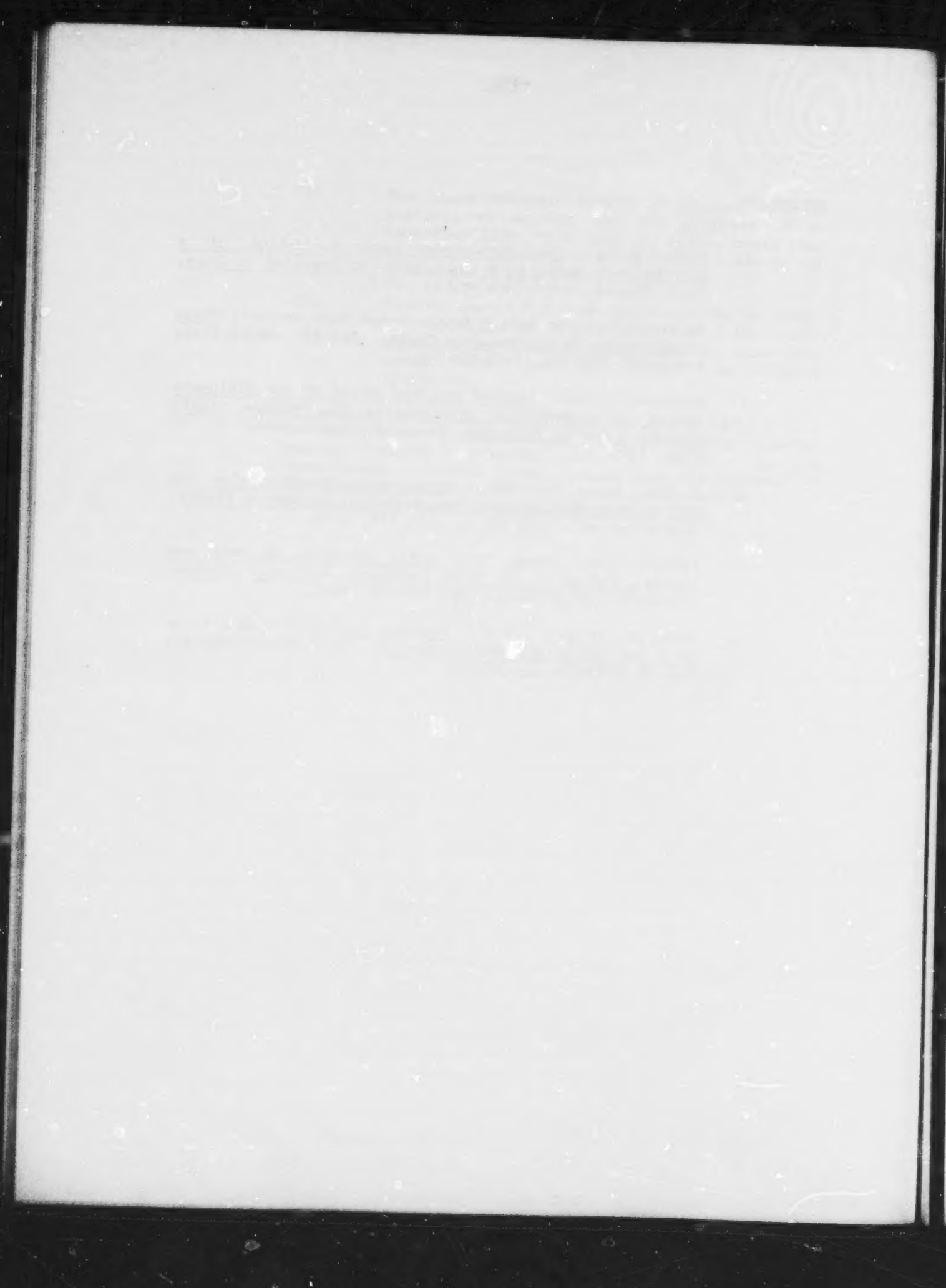
- i) A theoretical analysis of a tank with a burning relief valve flare exposed to cross-winds should be performed to obtain radiant exchange factors for such conditions.

- ii) The above analysis should be coupled with an analysis to account for the presence of an engulfing fire. The combined models could then be used to determine the worst case scenario for a tank-car fire event.
- iii) Further scale fire testing should be performed to validate the above analyses. The tests should be performed outdoors, and the cross-wind speeds and conditions should be closely monitored.

As a final note, the results of the present tests appear to validate the assumptions used to develop the Tank-Car thermal analysis computer program TNKCAR. In the development of TNKCAR it was assumed that the presence of the burning relief valve was not important because of the attenuating affects of the engulfing pool fire.

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- 2) Railroad Tank Car Safety Research and Test Project; Phase II Report on Full-Scale Fire Tests. AAR-RPI, RA-11-6-31, AAR-R-201, US6 AFI 17-75 ENG(BK).
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- 4) Becker, H.A.; Yamazaki; Entrainment, Momentum Flux and Temperature in Vertical Free Turbulent Diffusion Flames, Combustion and Flame 33, pp. 123-149, 1978.
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- 6) Tunc, M.; Venart, J.E.S.; Incident Radiation from a Flare to a Horizontal Cylinder - Part II, Fire Safety Journal, Vol. 8, 1984/85, pp. 89-96.



APPENDIX A
PLOTTED TEST RESULTS

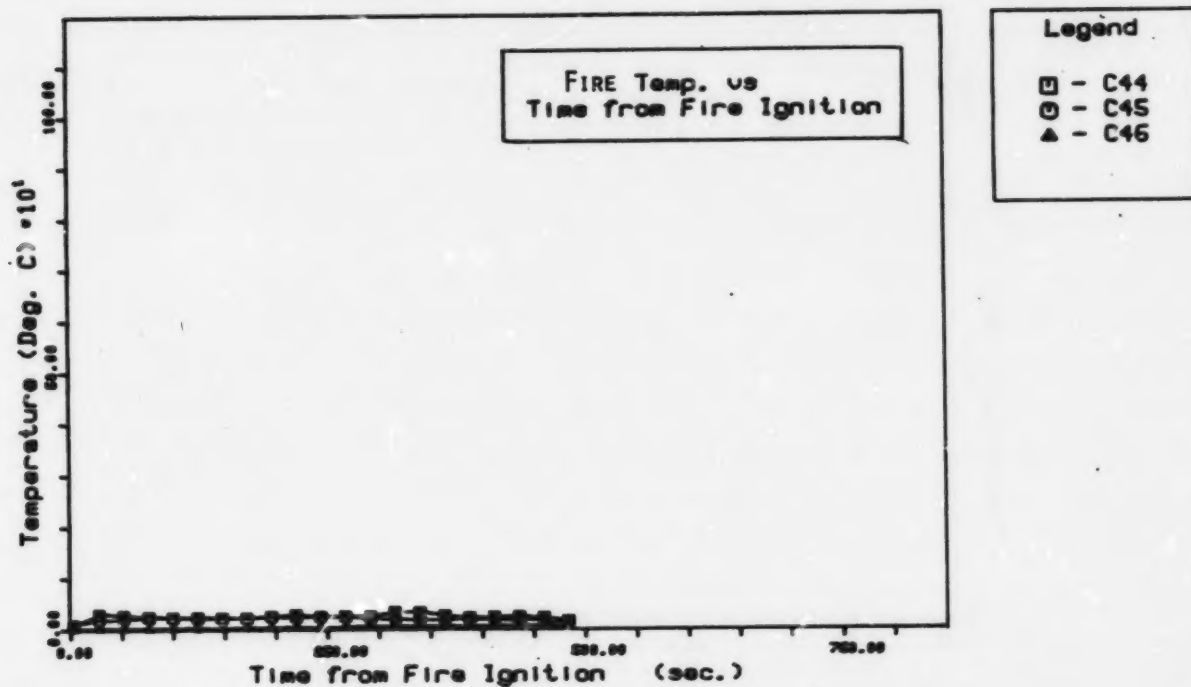


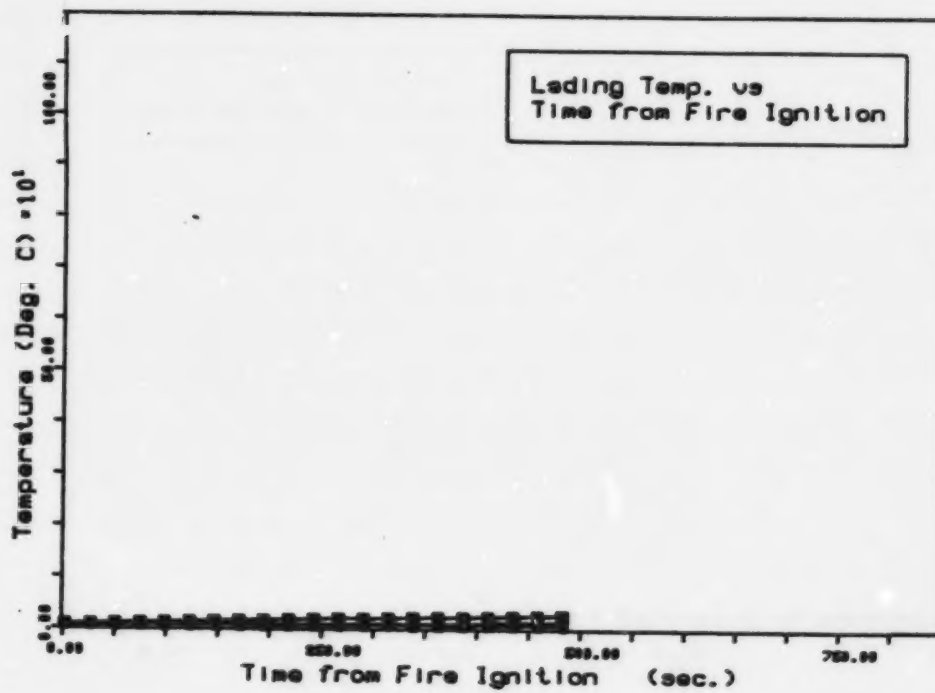
-A1-

FLARE TEST #1

December 5, 1984
(flare only)

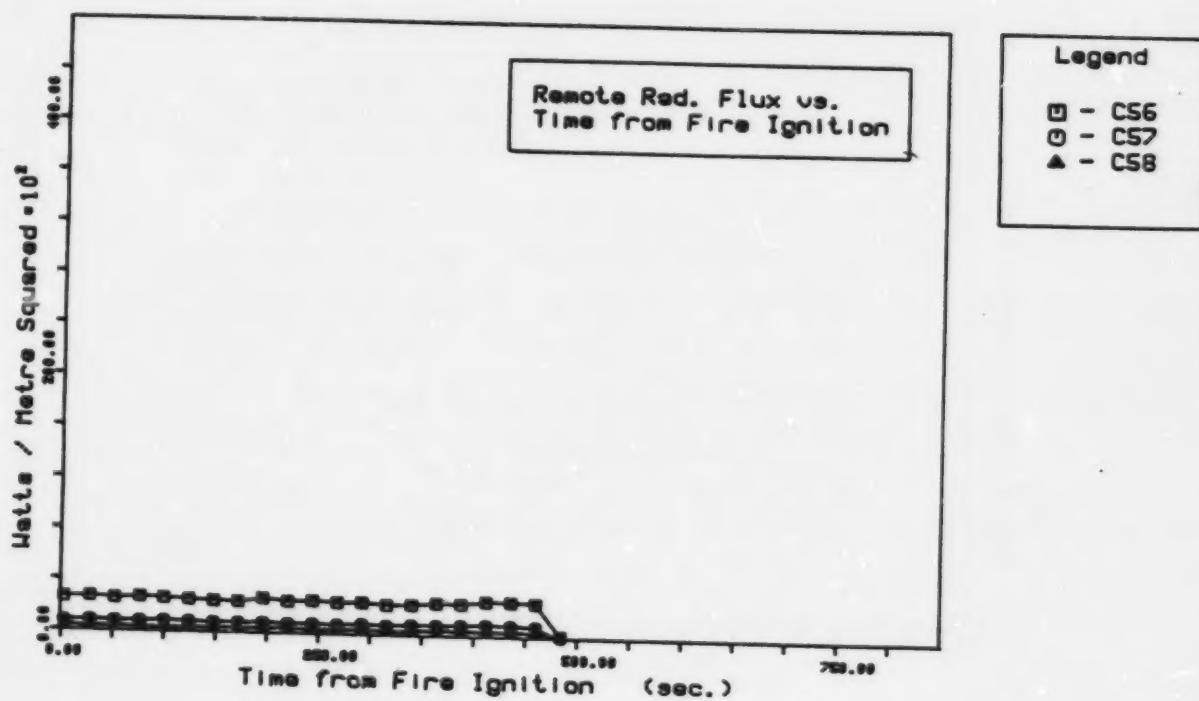


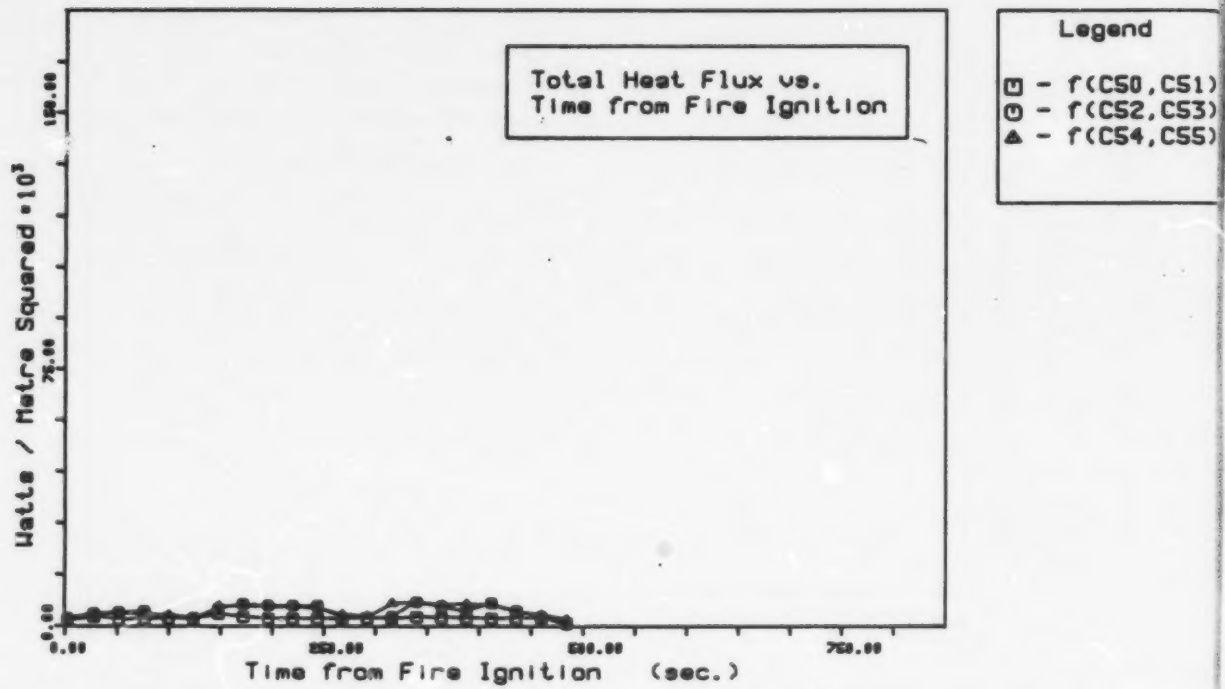


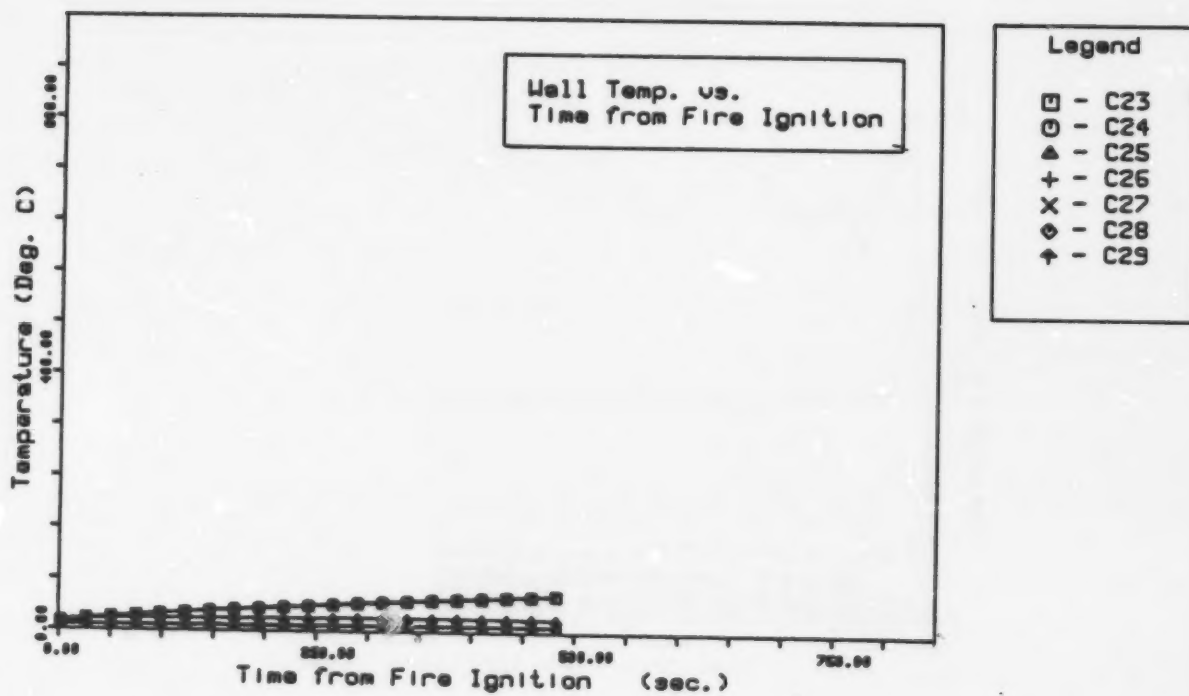


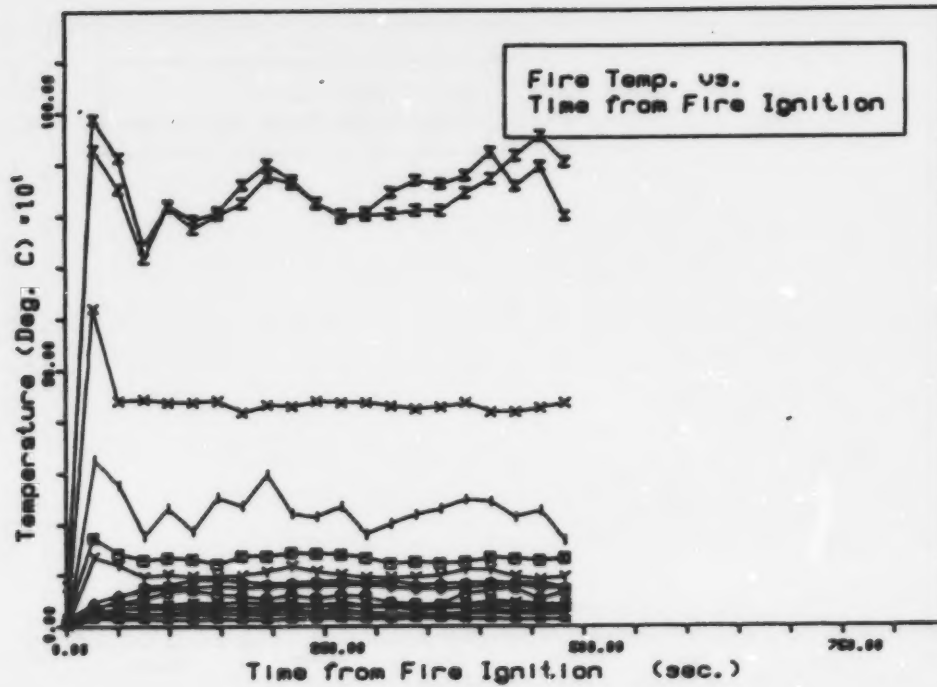
Legend

- - C30
- - C31
- △ - C32
- +
- X - C34
- ◇ - C35
- † - C36
- X - C37
- Z - C38
- Y - C39
- X - C40
- ※ - C41
- ⊗ - C42
- I - C43







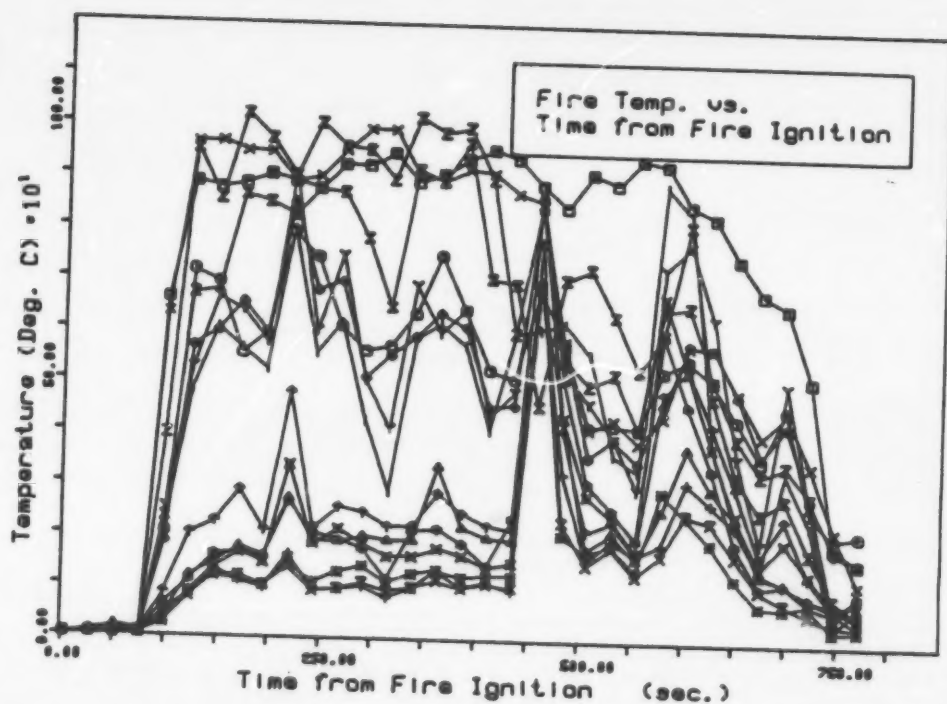


Legend

- - C6
- - C7
- △ - C8
- +
- x - C10
- ◇ - C11
- † - C12
- x - C13
- Z - C14
- Y - C15
- x - C16
- * - C17
- x - C18
- ! - C19
- - C20

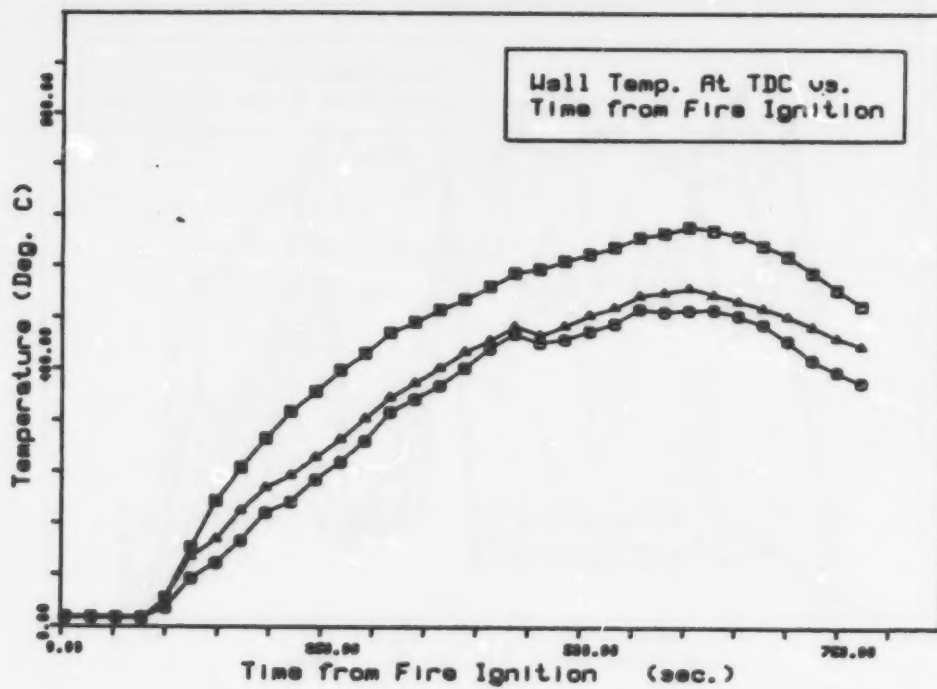
POOL FIRE TEST #1

December 5, 1984
(pool fire only)



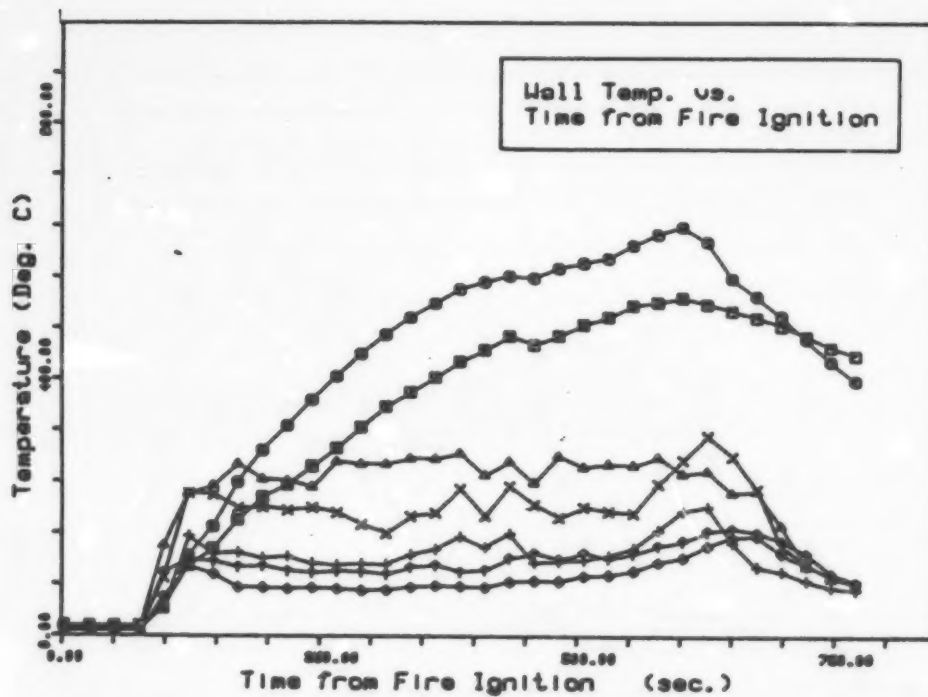
Legend

- - C6
- - C7
- △ - C8
- +
- X - C10
- ◇ - C11
- † - C12
- × - C13
- Z - C14
- Y - C15
- ✕ - C16
- * - C17
- Σ - C18
- ! - C19
- ⊙ - C20



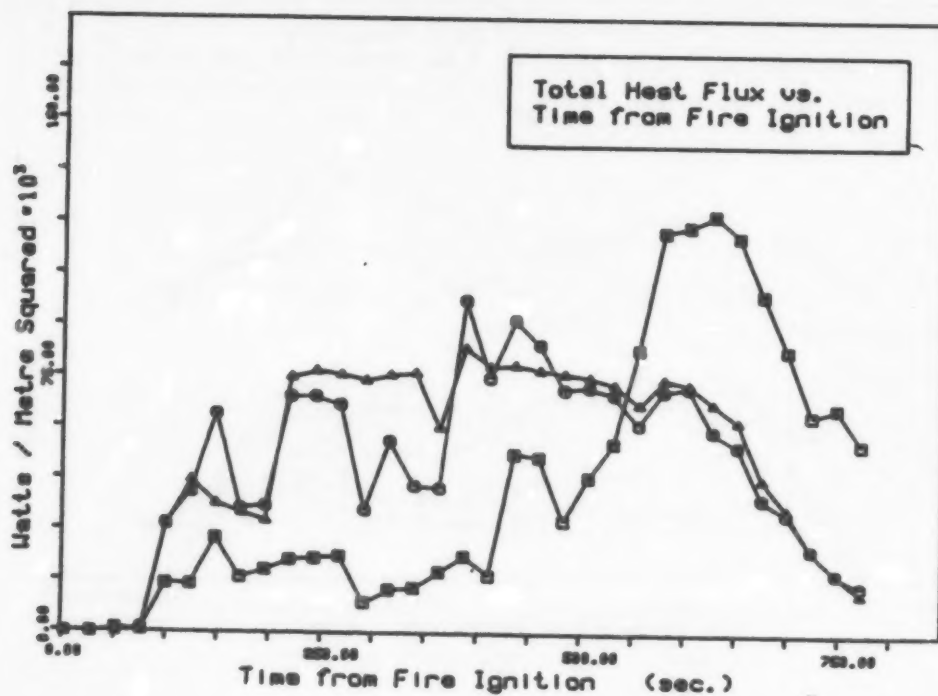
Legend

- - C21
- - C22
- ▲ - C23



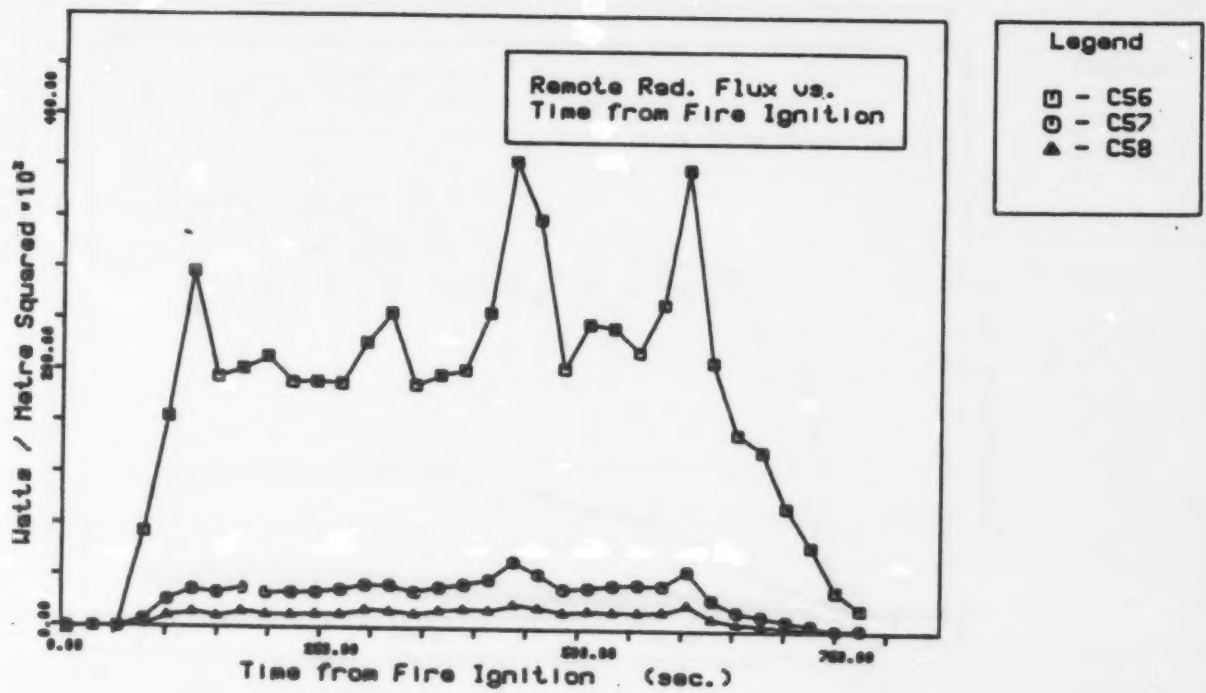
Legend

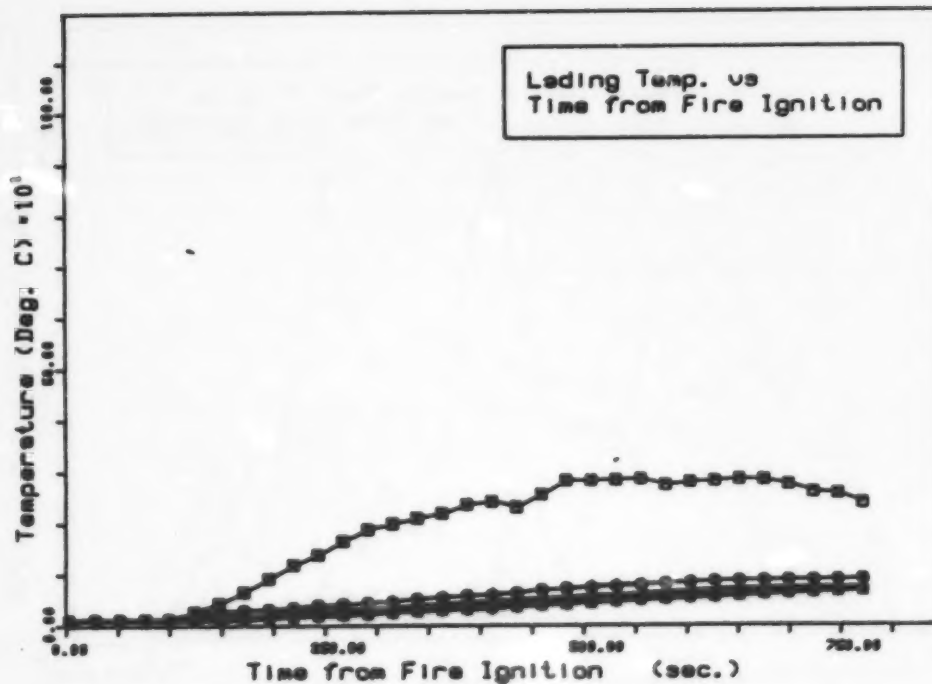
- - C23
- - C24
- △ - C25
- + - C26
- x - C27
- ◇ - C28
- † - C29



Legend

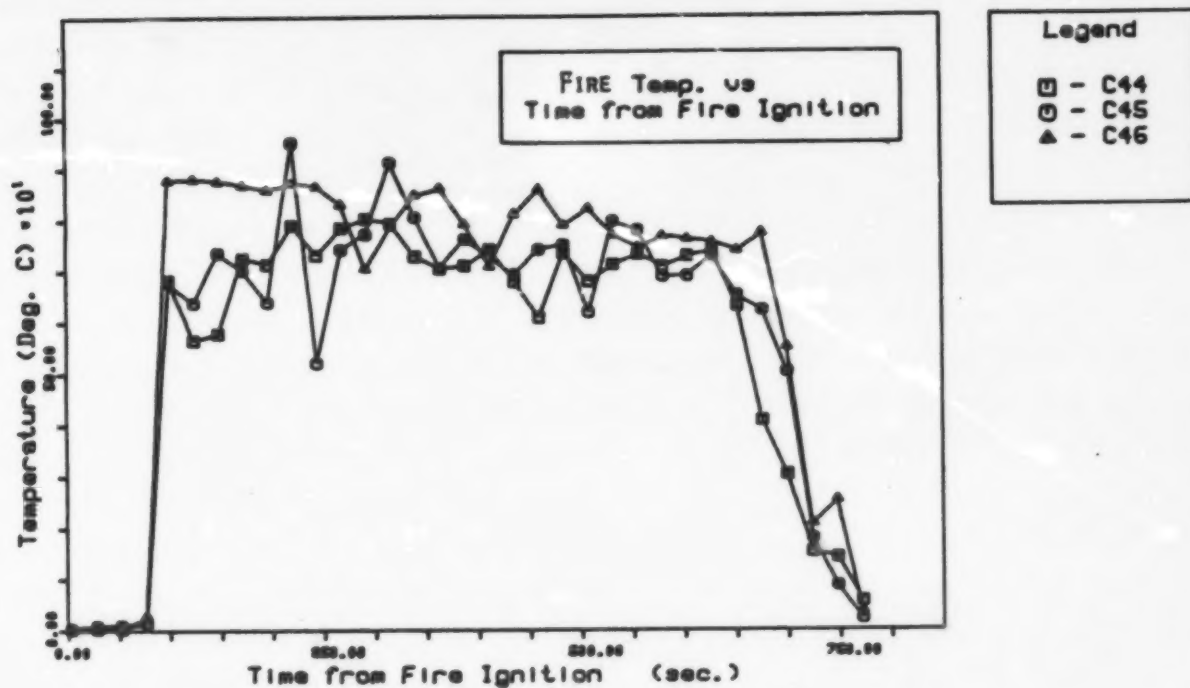
- - f(C50, C51)
- - f(C52, C53)
- ▲ - f(C54, C55)





Legend

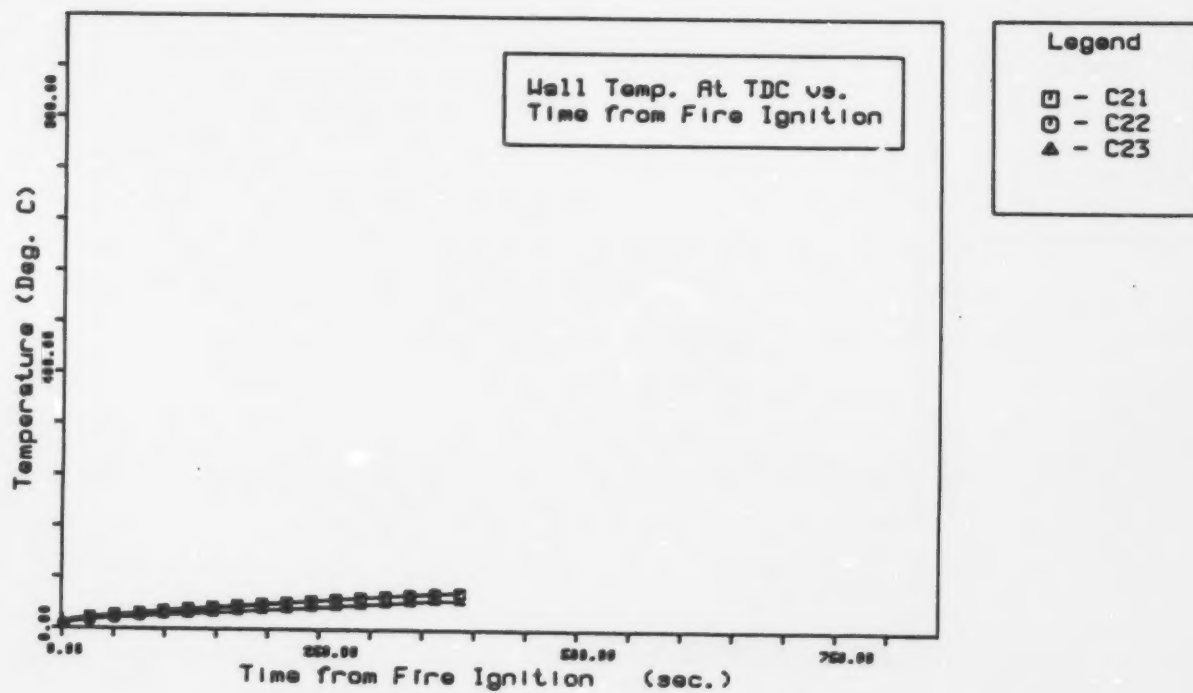
- - C30
- - C31
- △ - C32
- + - C33
- x - C34
- ◇ - C35
- † - C36
- x - C37
- Z - C38
- Y - C39
- x - C40
- ⌘ - C41
- ⌘ - C42
- I - C43

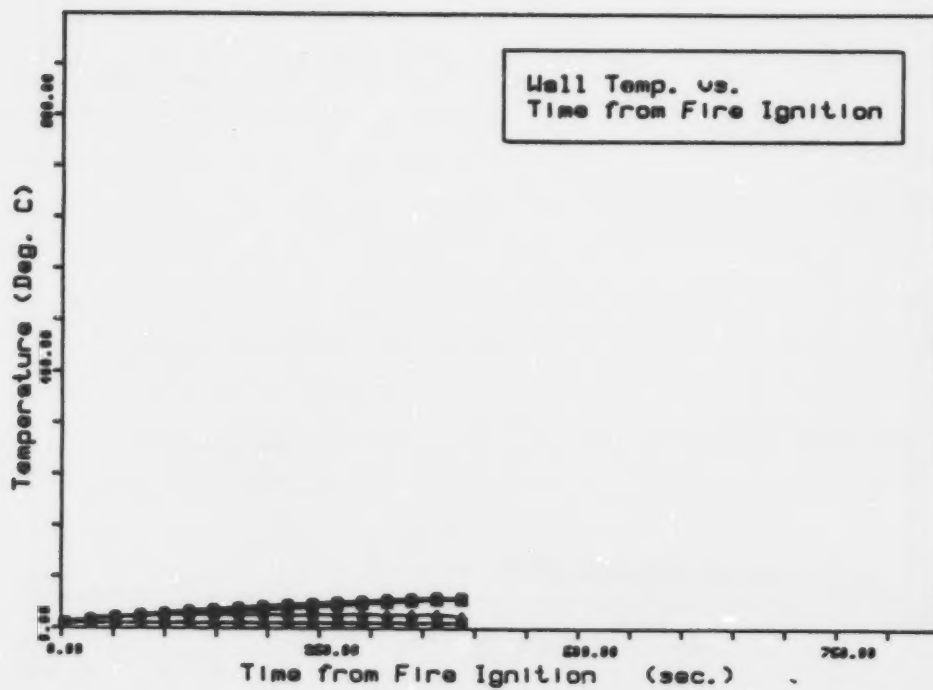


FLARE TEST #2

December 19, 1984
(flare only)

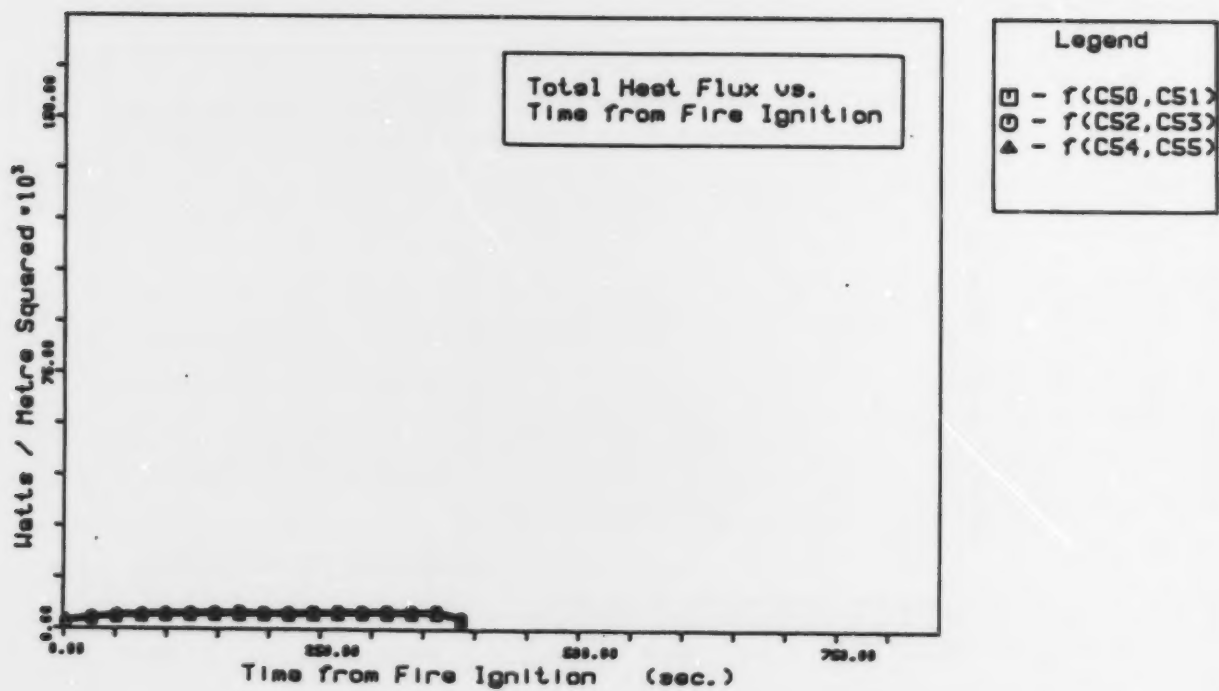


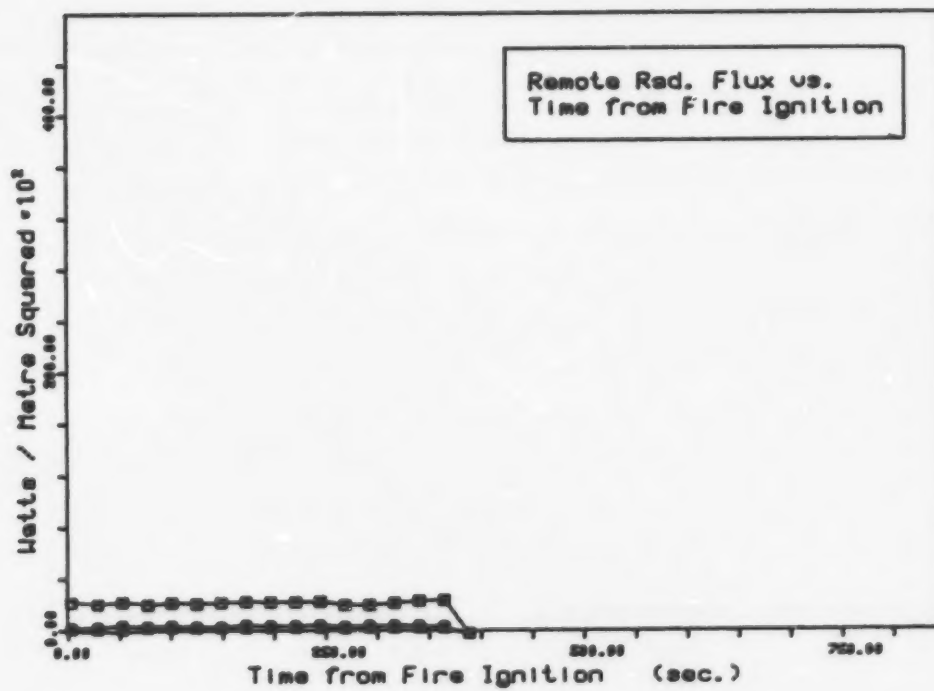




Legend

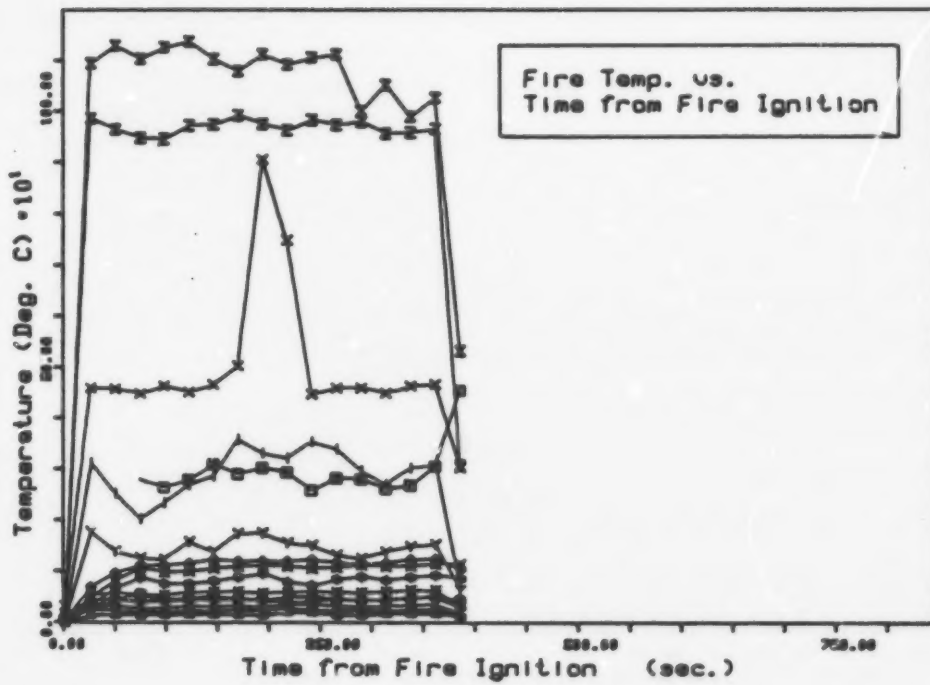
- - C23
- ⊖ - C24
- ▲ - C25
- ⊕ - C26
- × - C27
- ◇ - C28
- ↑ - C29





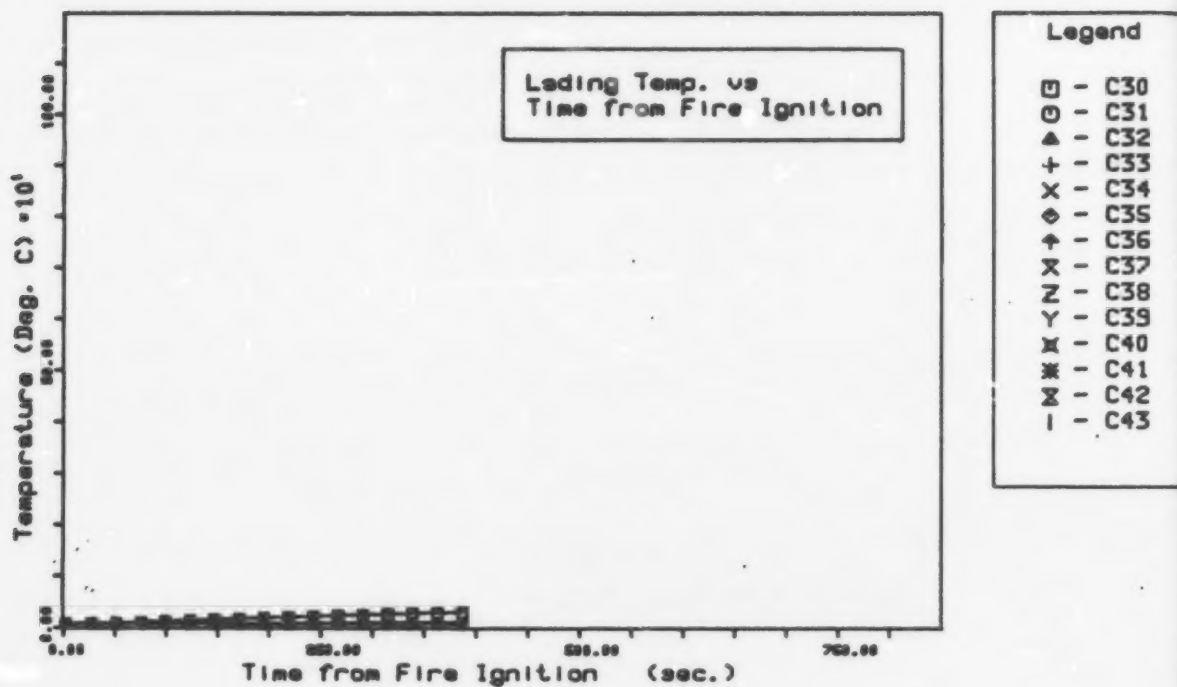
Legend

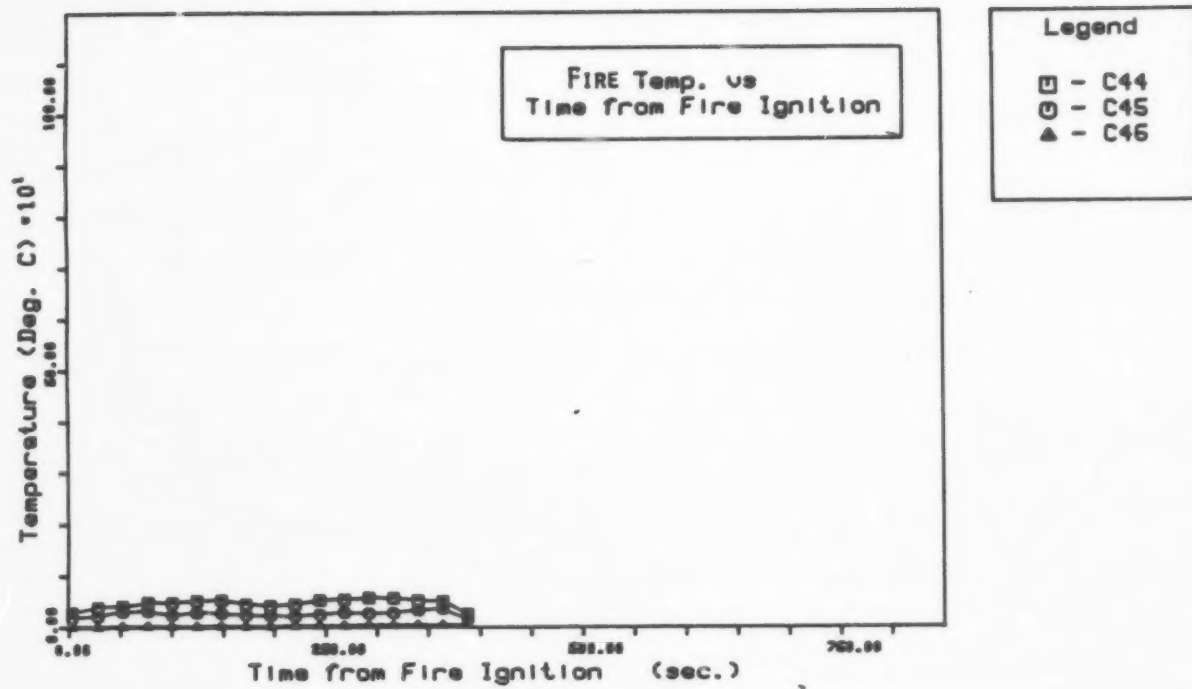
- - CS6
- - CS7
- ▲ - CS8



Legend

- - C6
- - C7
- △ - C8
- +
- X - C10
- ◇ - C11
- † - C12
- × - C13
- Z - C14
- Y - C15
- x - C16
- * - C17
- Σ - C18
- I - C19
- - C20



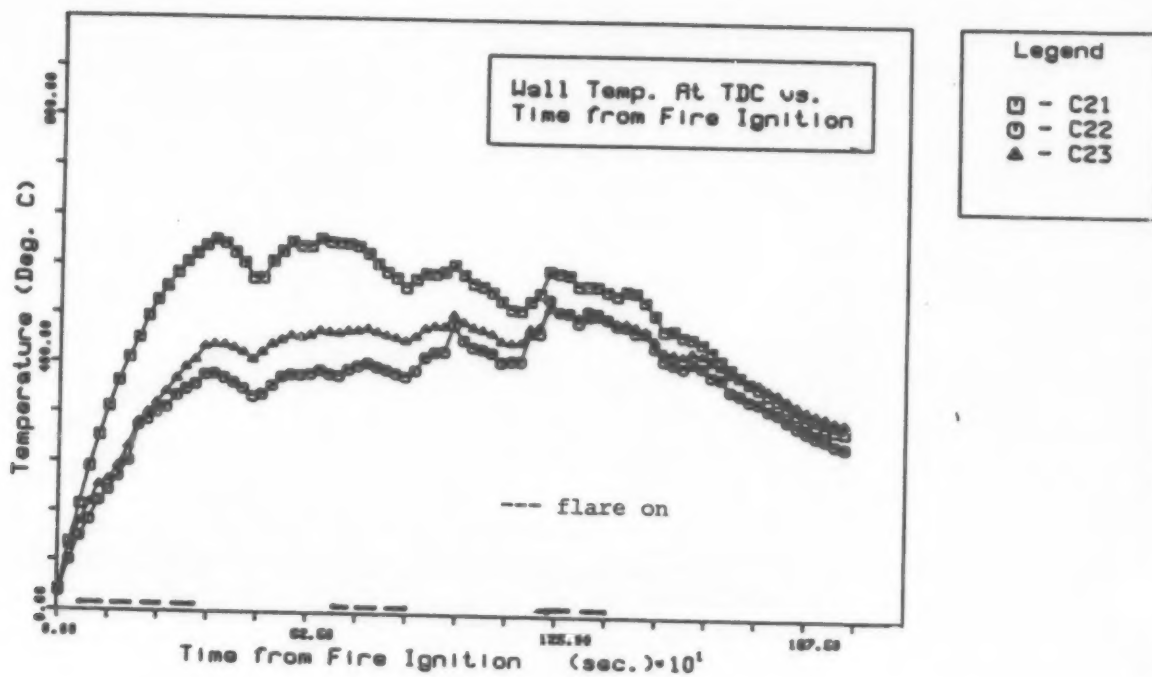


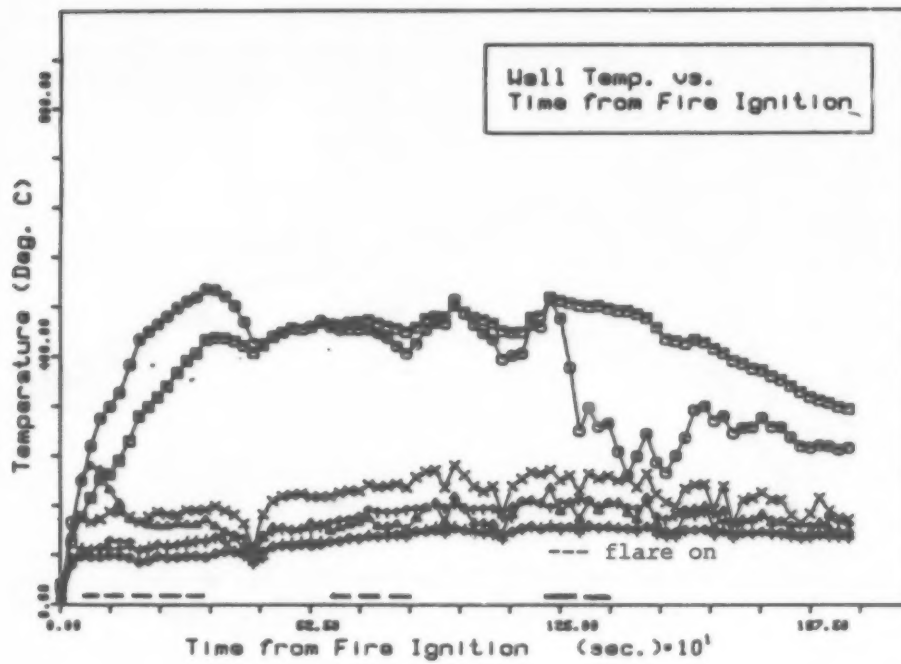


POOL AND FLARE TEST #1

December 19, 1984
(pool fire and flare)

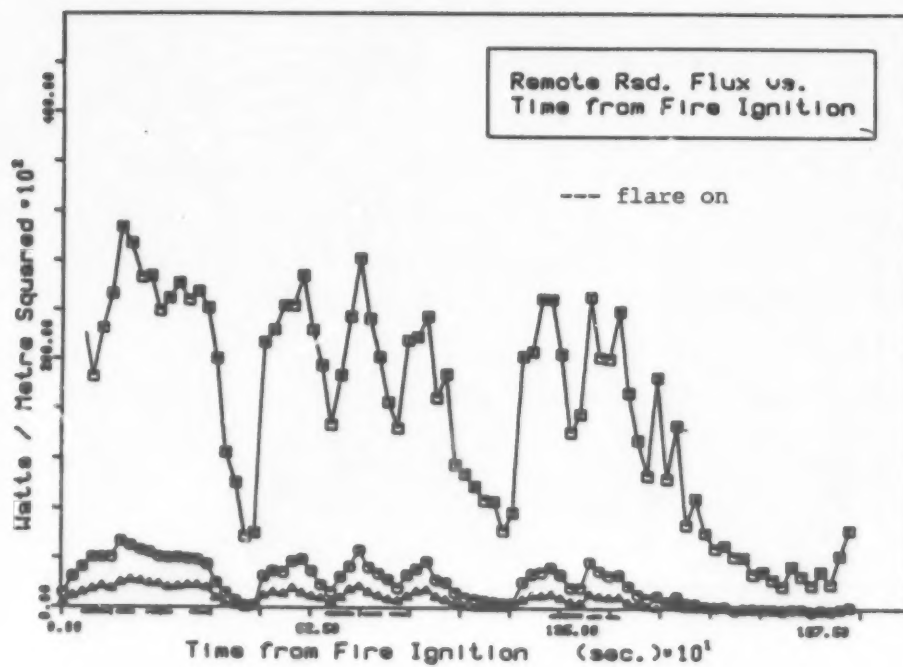






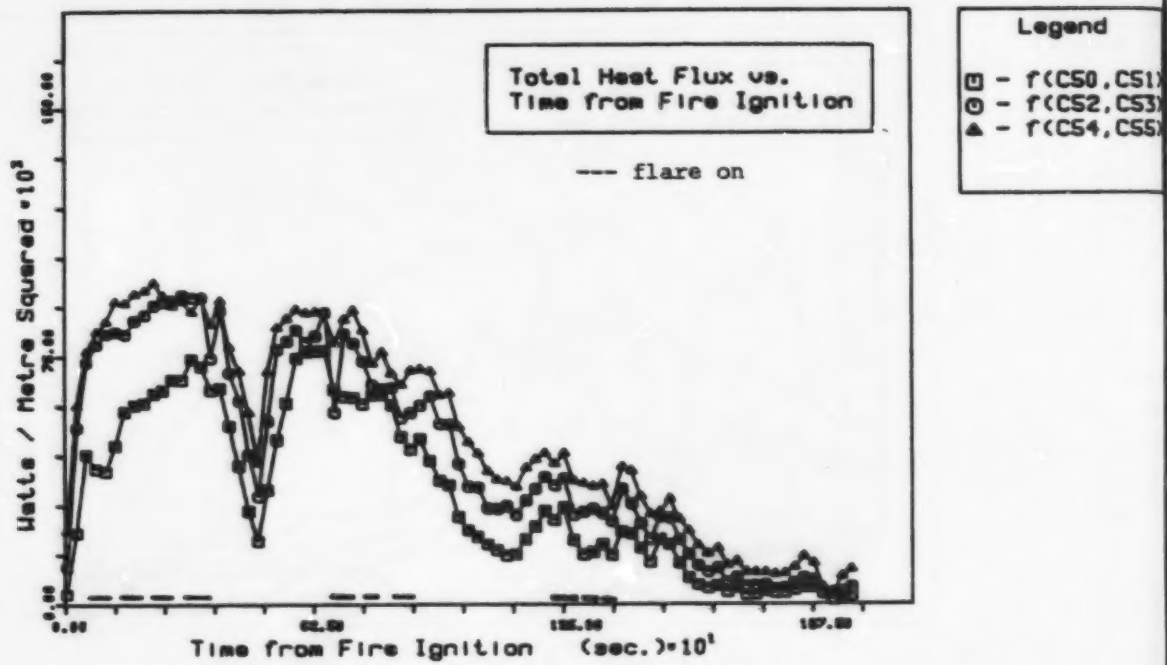
Legend

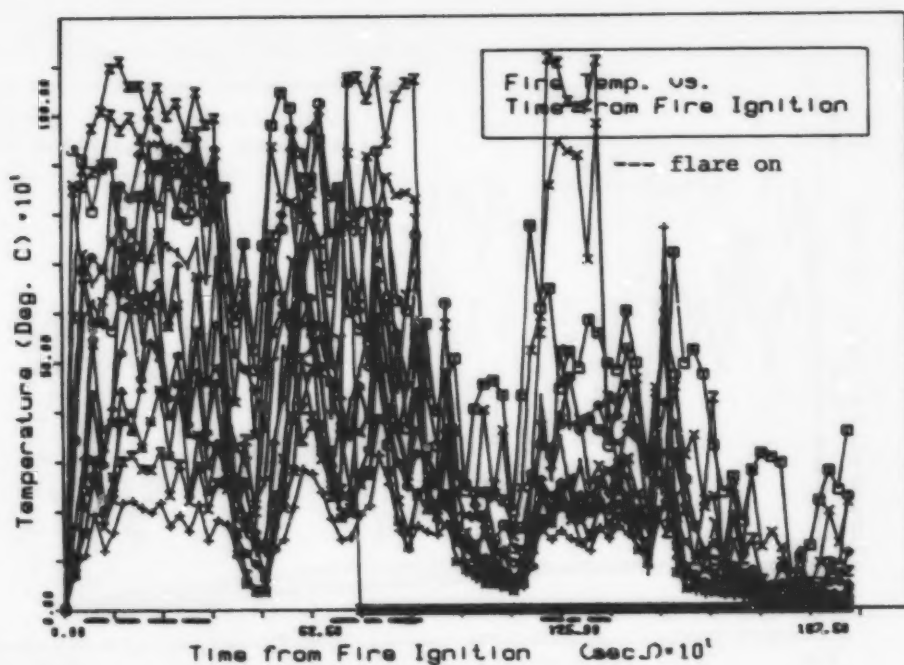
- - C23
- - C24
- ▲ - C25
- +
- X - C27
- ◇ - C28
- † - C29



Legend

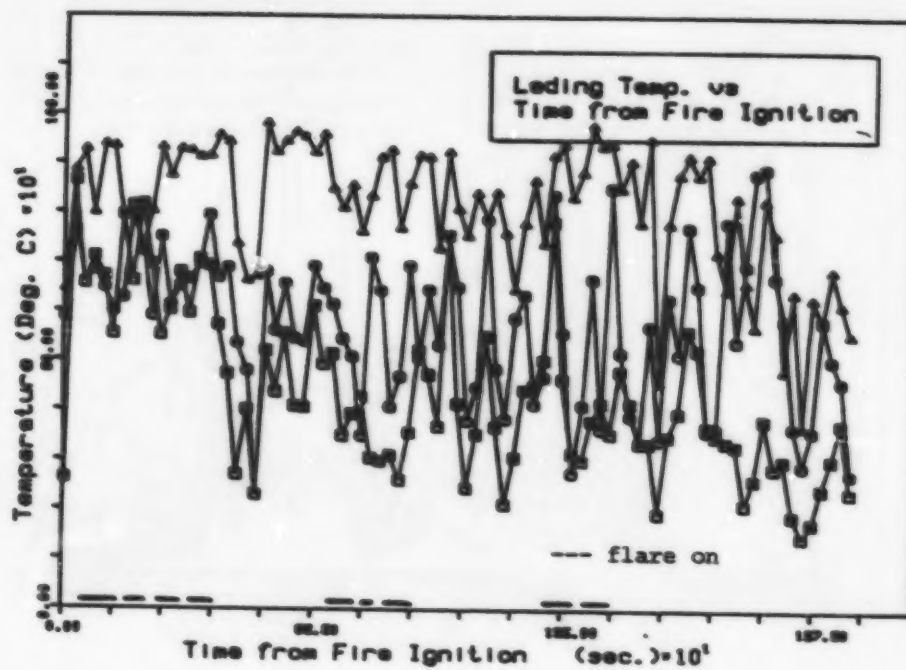
- - C56
- - C57
- △ - C58





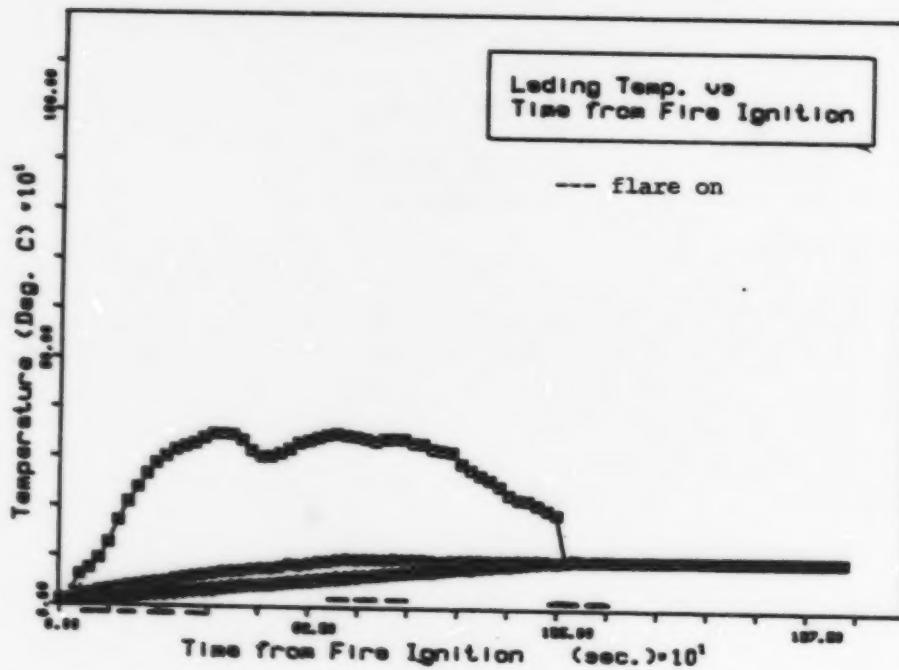
Legend

- - C6
- - C7
- △ - C8
- +
- X - C10
- ◇ - C11
- ⊕ - C12
- × - C13
- Z - C14
- Y - C15
- ⊗ - C16
- ⊗ - C17
- ⊗ - C18
- ! - C19
- ⊗ - C20



Legend

- - C44
- - C45
- △ - C46



Legend

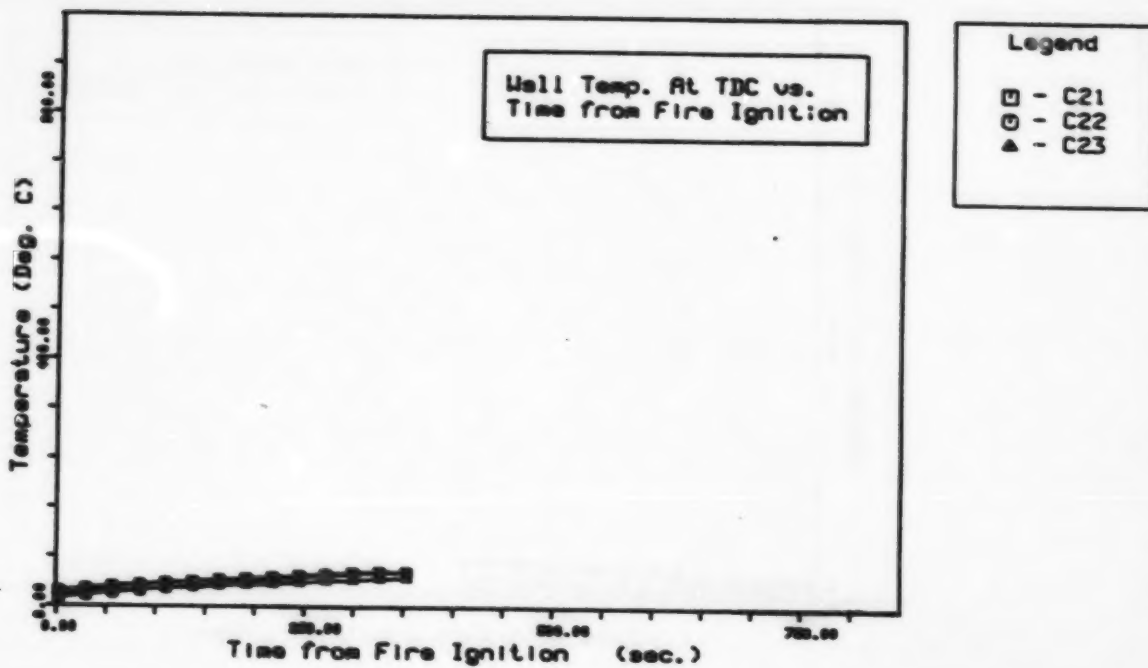
- - C30
- - C31
- △ - C32
- +
- X - C34
- ◇ - C35
- † - C36
- X - C37
- Z - C38
- Y - C39
- X - C40
- ≡ - C41
- Σ - C42
- I - C43

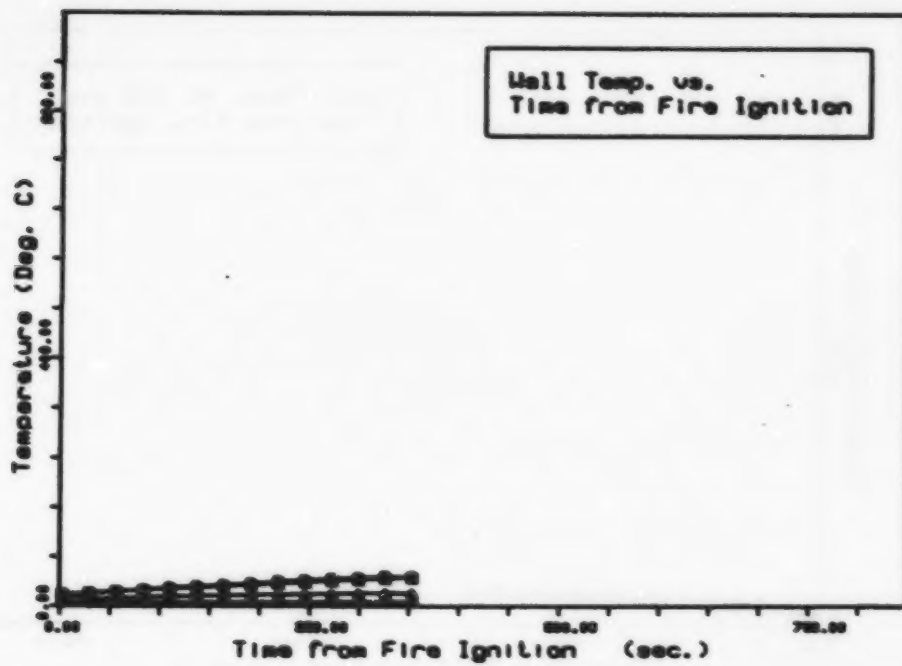


-A32-

FLARE TEST #3

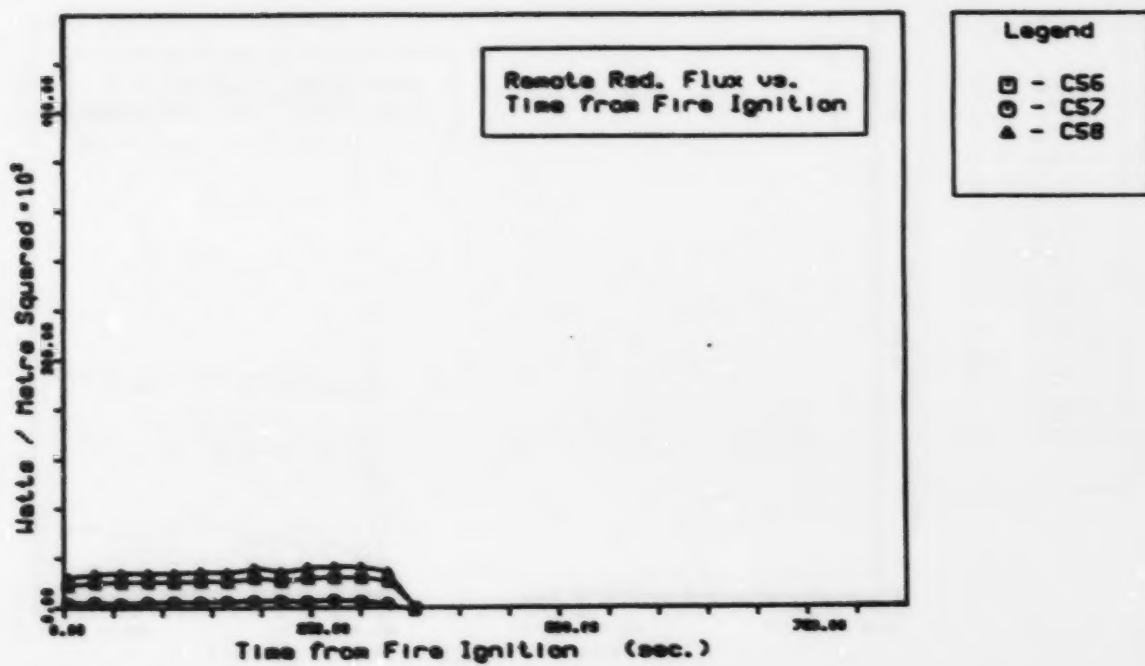
January 31, 1985
(flare only)

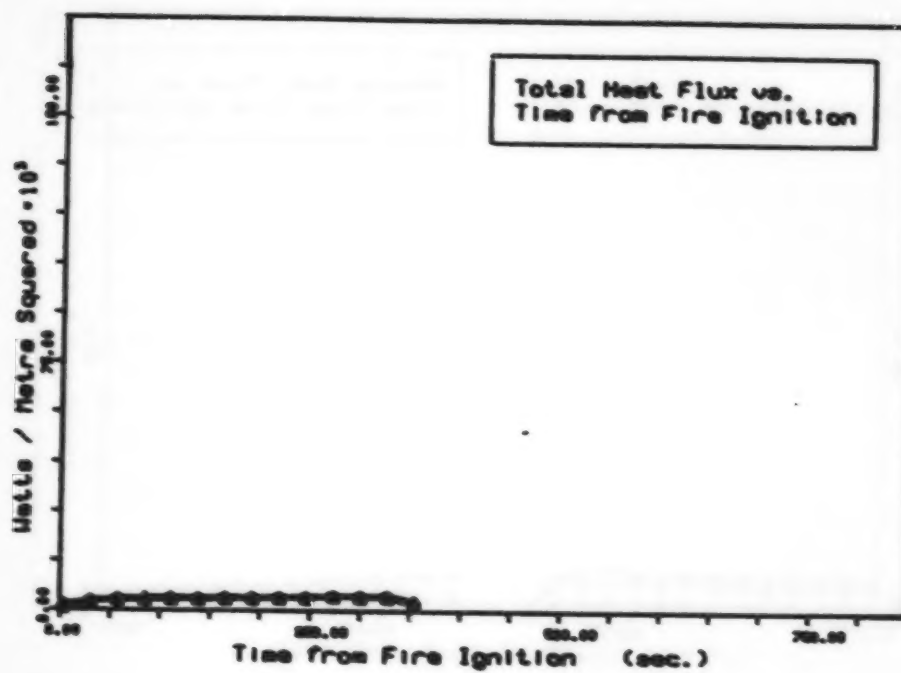




Legend

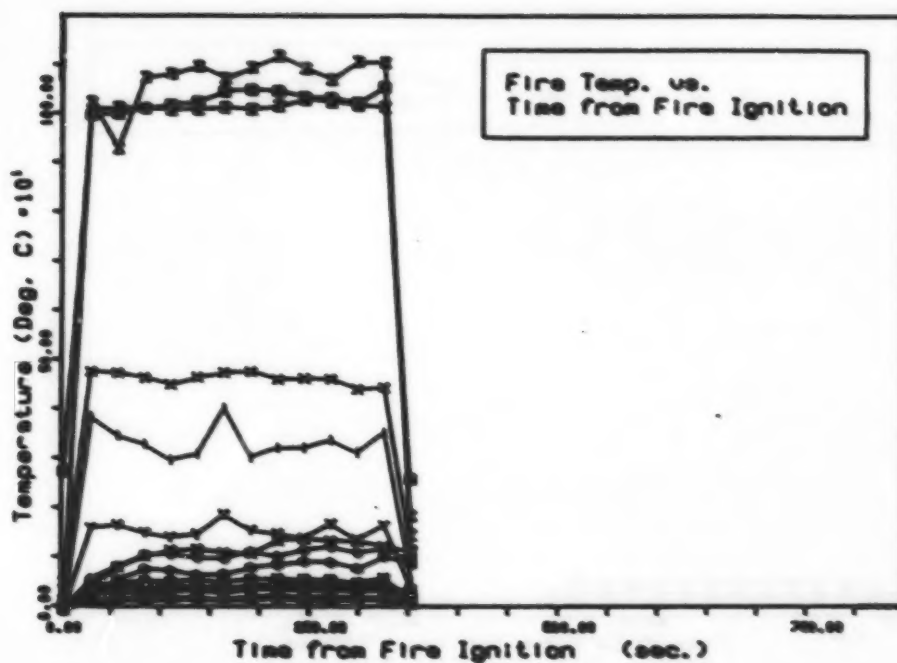
- - C23
- - C24
- △ - C25
- +
- x - C27
- ◇ - C28
- † - C29





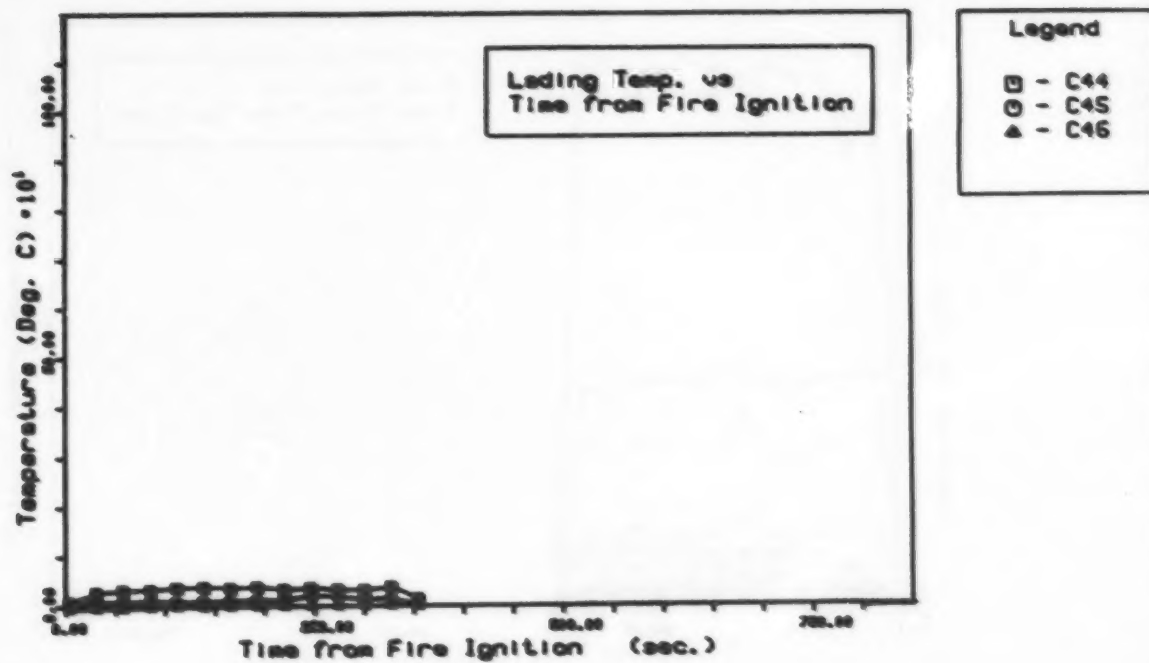
Legend

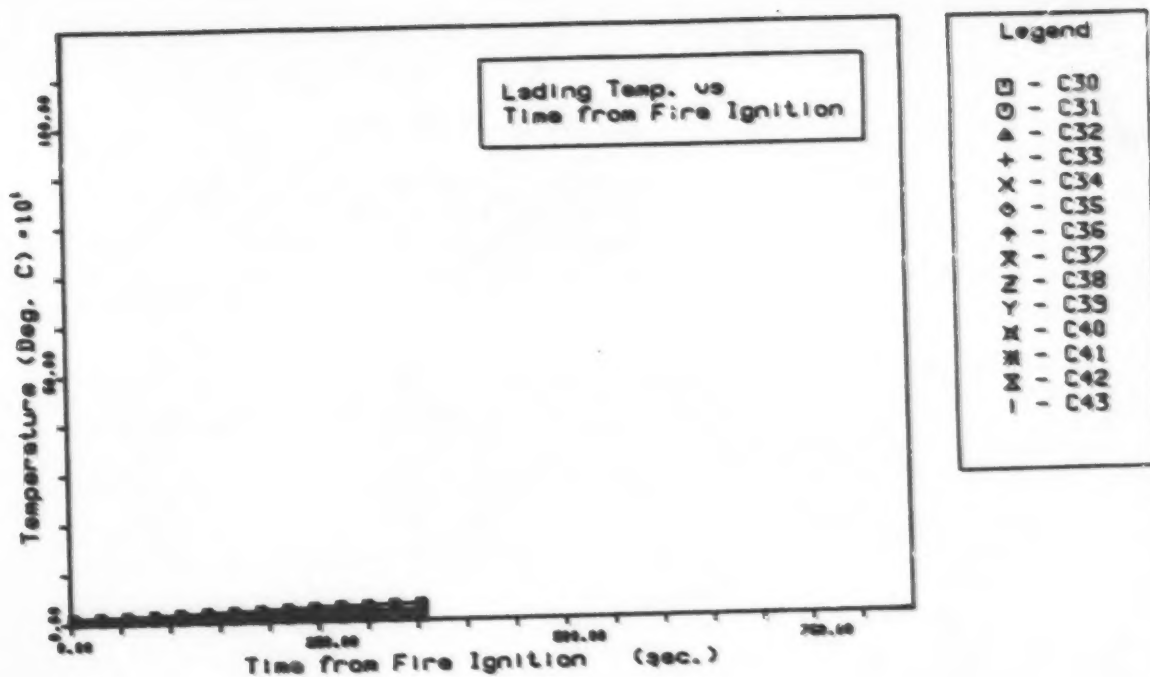
- - f(CS0,CS1)
- - f(CS2,CS3)
- △ - f(CS4,CS5)



Legend

- - C6
- - C7
- △ - C8
- + - C9
- x - C10
- ◇ - C11
- † - C12
- × - C13
- z - C14
- y - C15
- κ - C16
- ≡ - C17
- ≡ - C18
- i - C19
- ⊙ - C20

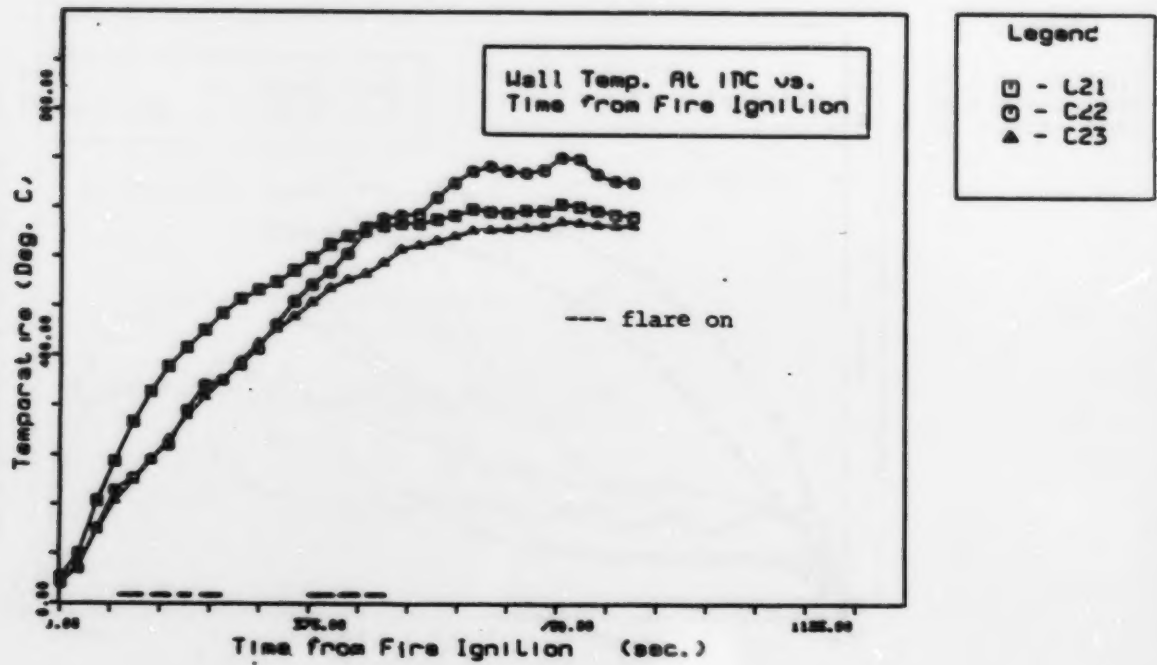


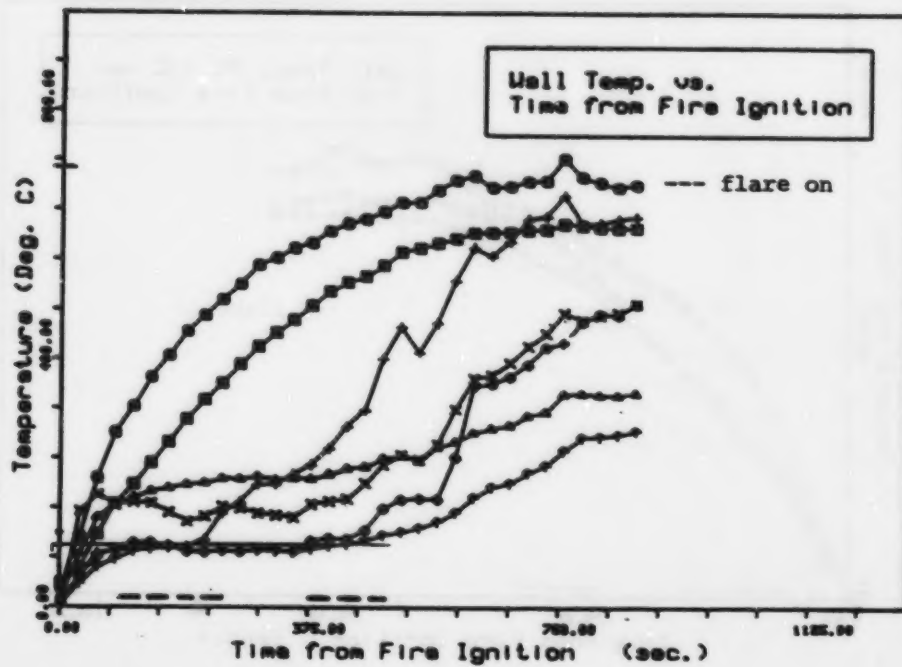


POOL AND FLARE TEST #2

January 31, 1985
(pool fire and flare)

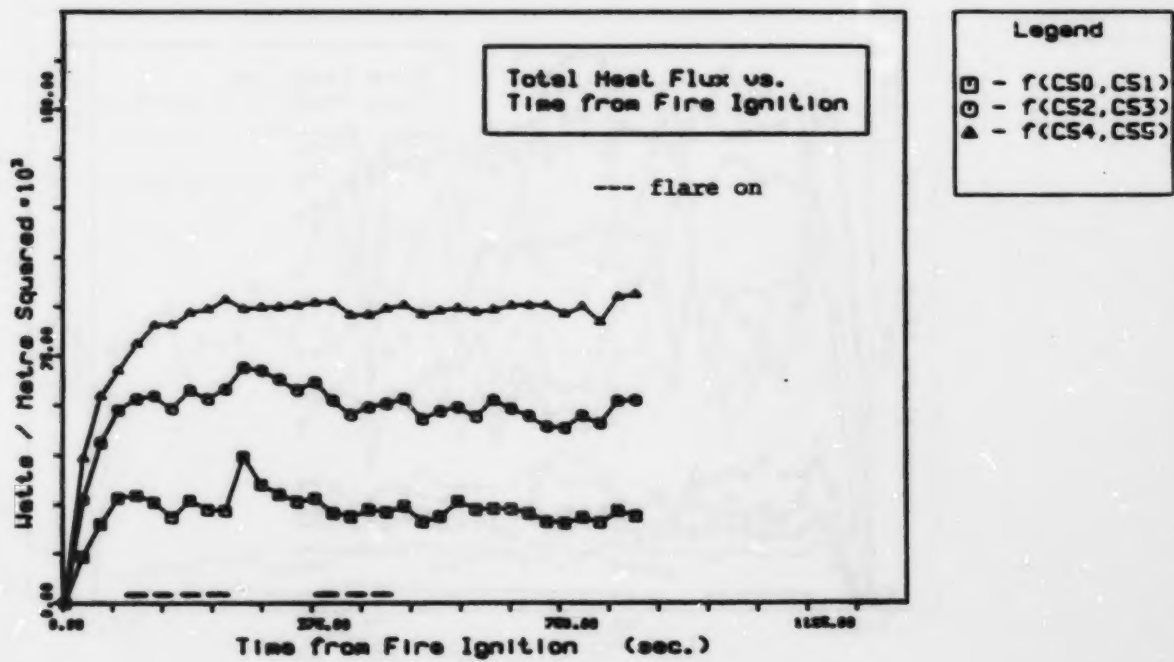


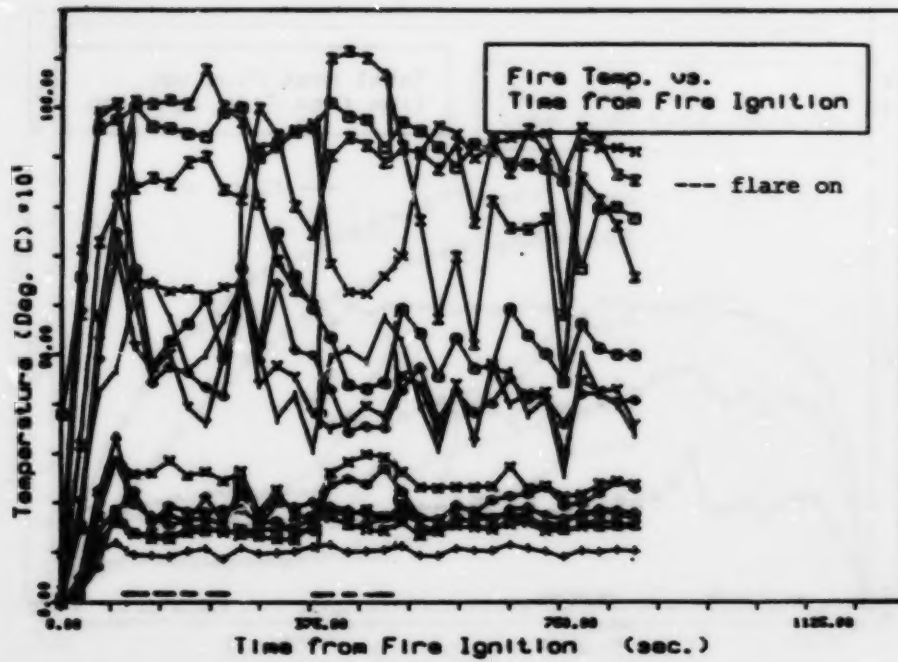




Legend

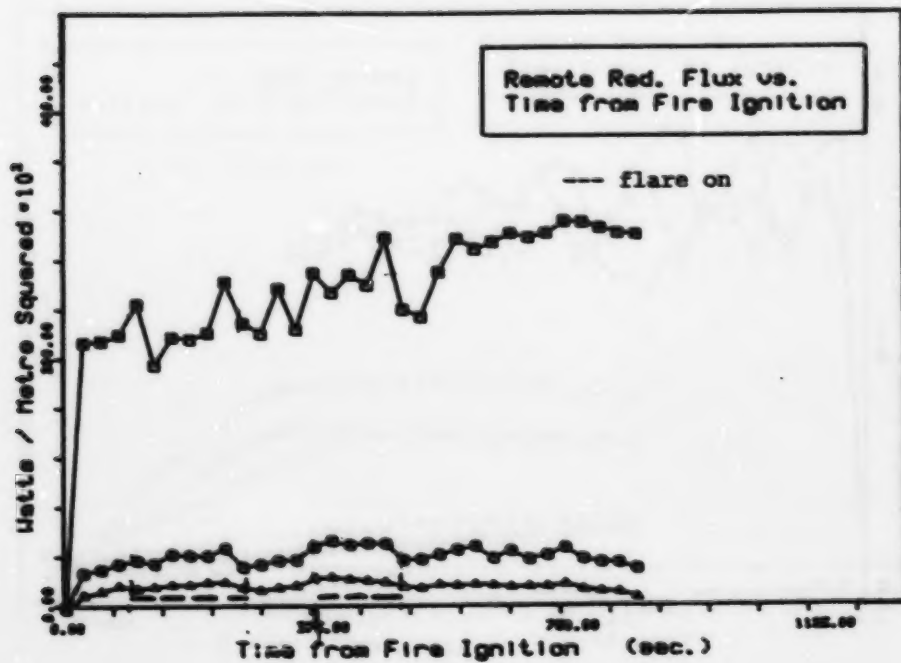
- - C23
- - C24
- △ - C25
- +
- x - C27
- ◇ - C28
- † - C29





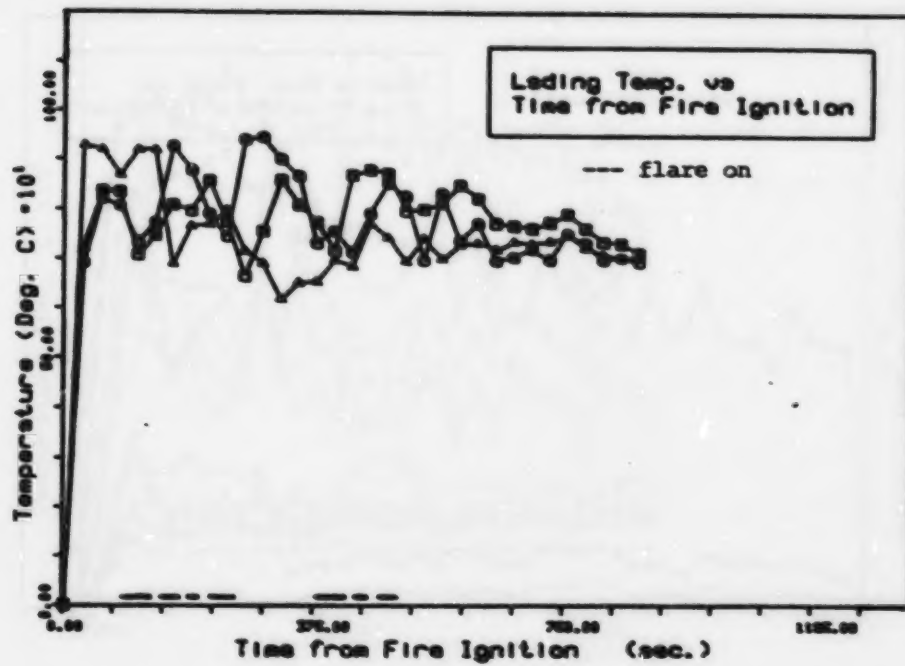
Legend

- - C6
- - C7
- △ - C8
- +
- x - C10
- ◇ - C11
- ⊕ - C12
- x - C13
- Z - C14
- Y - C15
- X - C16
- ⊗ - C17
- ⊗ - C18
- I - C19
- - C20



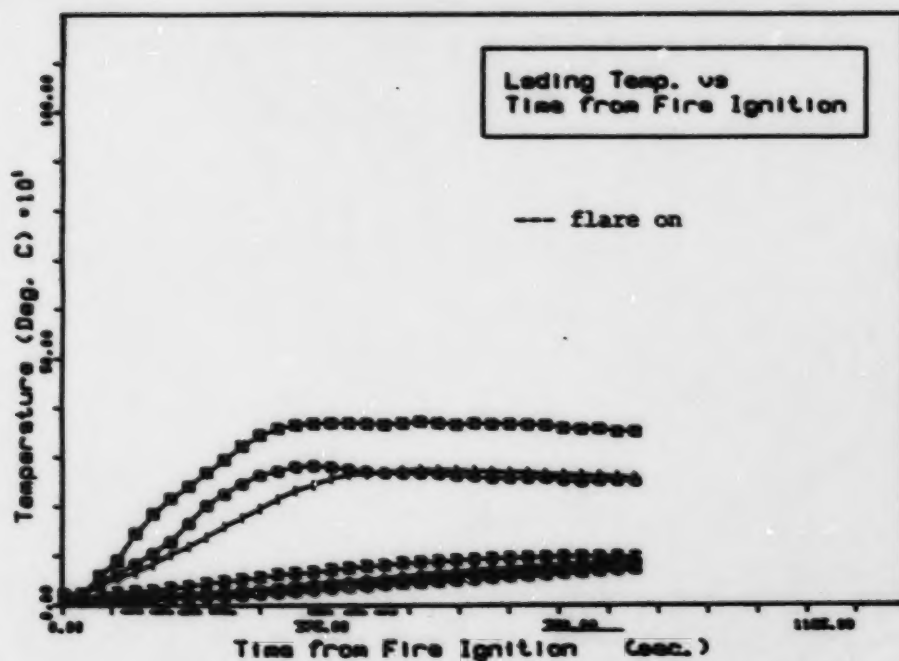
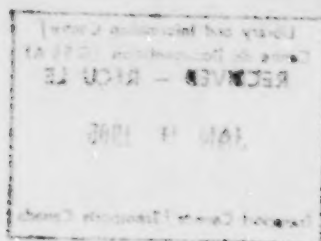
Legend

- - CS6
- - CS7
- △ - CS8



Legend

- - C44
- - C45
- △ - C46



Legend

- - C30
- - C31
- △ - C32
- + - C33
- x - C34
- ◇ - C35
- ⋈ - C36
- ⋈ - C37
- z - C38
- y - C39
- ⋈ - C40
- ⋈ - C41
- ⋈ - C42
- i - C43